Optimization of the High-Brightness Beam Performance of the CERN PSB with H^- Injection

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BE Seminar

07/07/2023

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CERN

Overview

Introduction

Part I: injecting beam from Linac4

Part II: maintaining beam properties in PSB

Part III: pushing the limits of PSB

Conclusions

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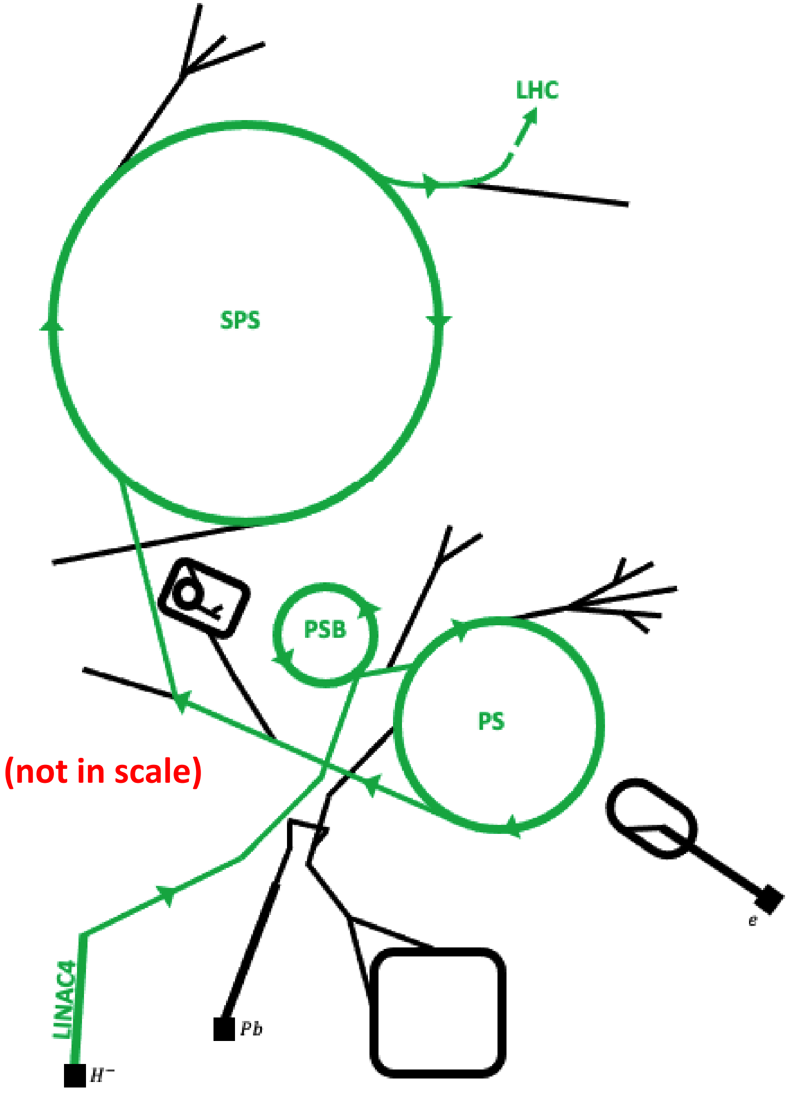
LHC Injectors Upgrade (LIU) project

LHC produces particle collisions for high-energy experiments.



LHC plans to increase collision rate.

Upgrade machine	Enhance incoming beams
HL-LHC project (2026-2028)	LIU project (2019-2021)

LHC requires **brighter beams**:

1) More particles (i.e. higher beam **intensity**)
2) Denser particles (i.e. smaller beam **emittance**)

Injectors could not satisfy LHC requirements → major **upgrades within LIU project**.

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Injectors limitations

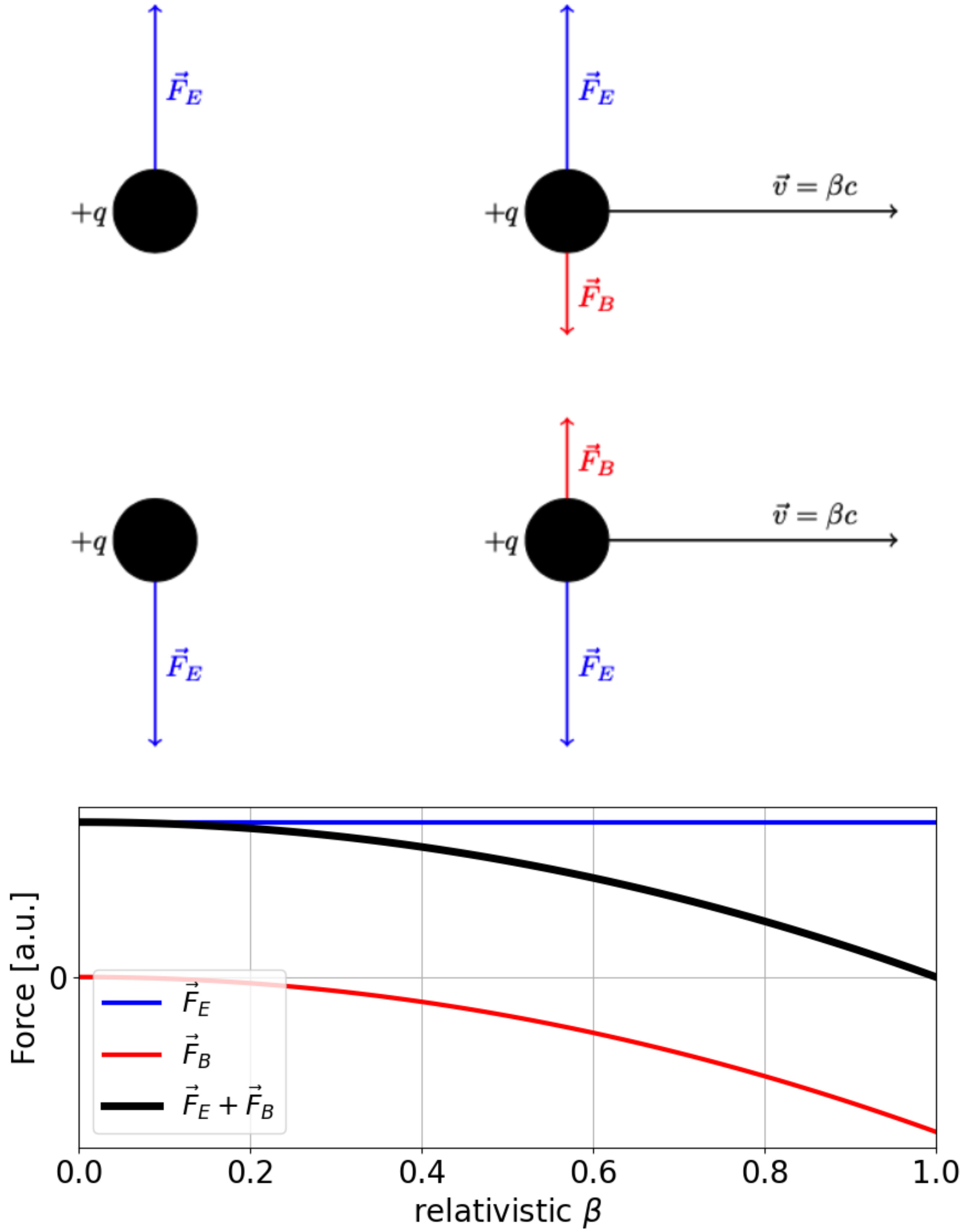
LIU upgrades essential: injectors operated in their **brightness limit**.

- Low energy accelerators (PSB, PS) mostly limited by space charge effects.

Space charge refers to the Coulomb interaction of charged particles.

- More particles/area → stronger space charge.

Space charge reduces at higher energies → **energy upgrades for PSB & PS** to double brightness for same space charge.



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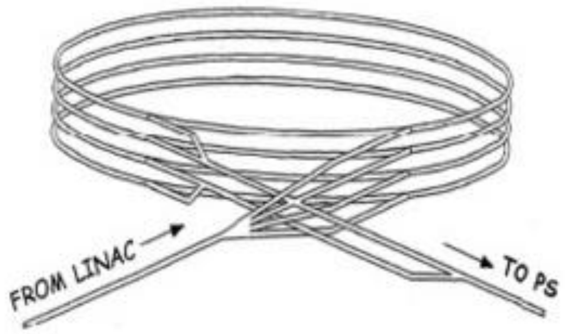
PSB upgrades

PSB: small, circular, p^+ accelerator with 4 identical rings.



PSB energy upgrade achieved by:

- Replacement of Linac2 (50 MeV) by **Linac4 (160 MeV)**.
- Magnets power supply and extraction upgrade (1.4 GeV to **2 GeV**).

Linac4 accelerates H^-: new charge-exchange injection for PSB ($H^- \rightarrow p^+$).

First time **injection of Linac4 H^-** in entirely **upgraded PSB**:

New effects to study, new challenges to overcome: **need of optimizations!**

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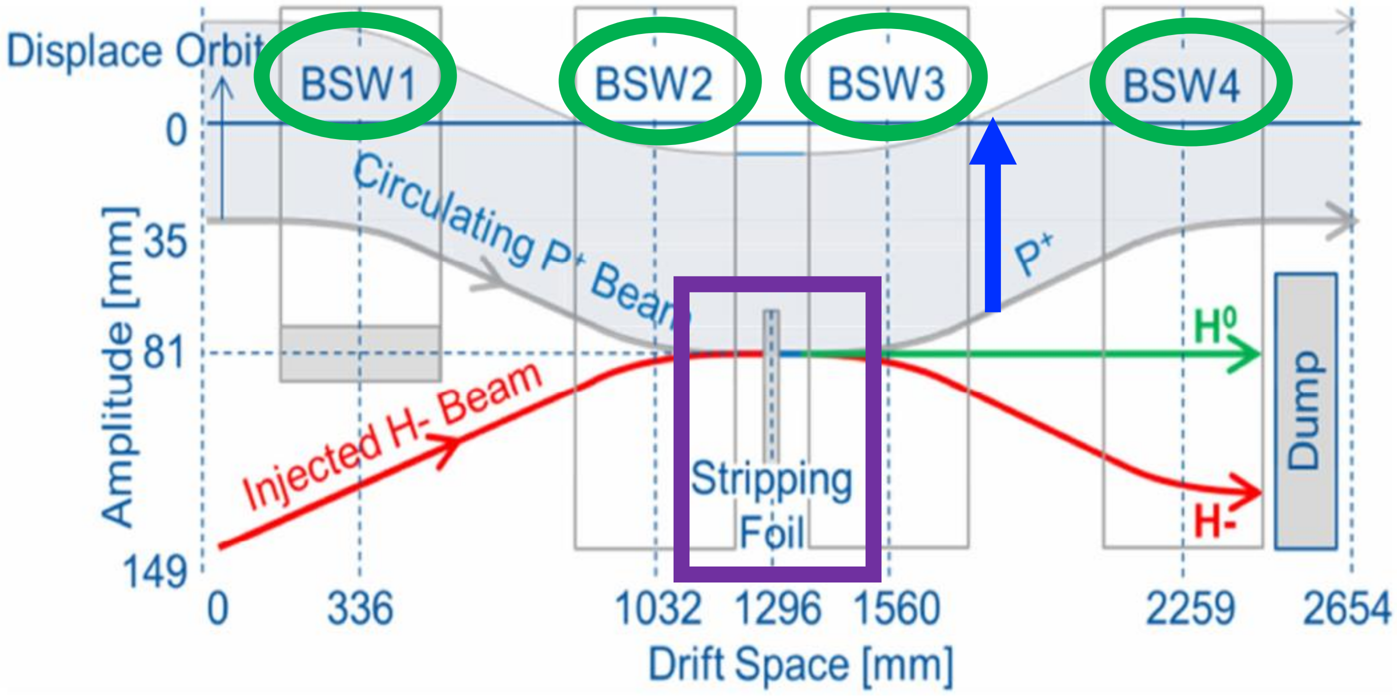
From PSB injection to extraction ↓

H^- injection

Charge-exchange injection system:

- $H^- \rightarrow p^+$ by crossing **thin foil**.
- Local **magnets** put p^+ in orbit around PSB.
- Design of local **orbit bump** allows multi-turn injection: **more** and **denser** particles!
- Local bump dynamically decays to zero after injection.

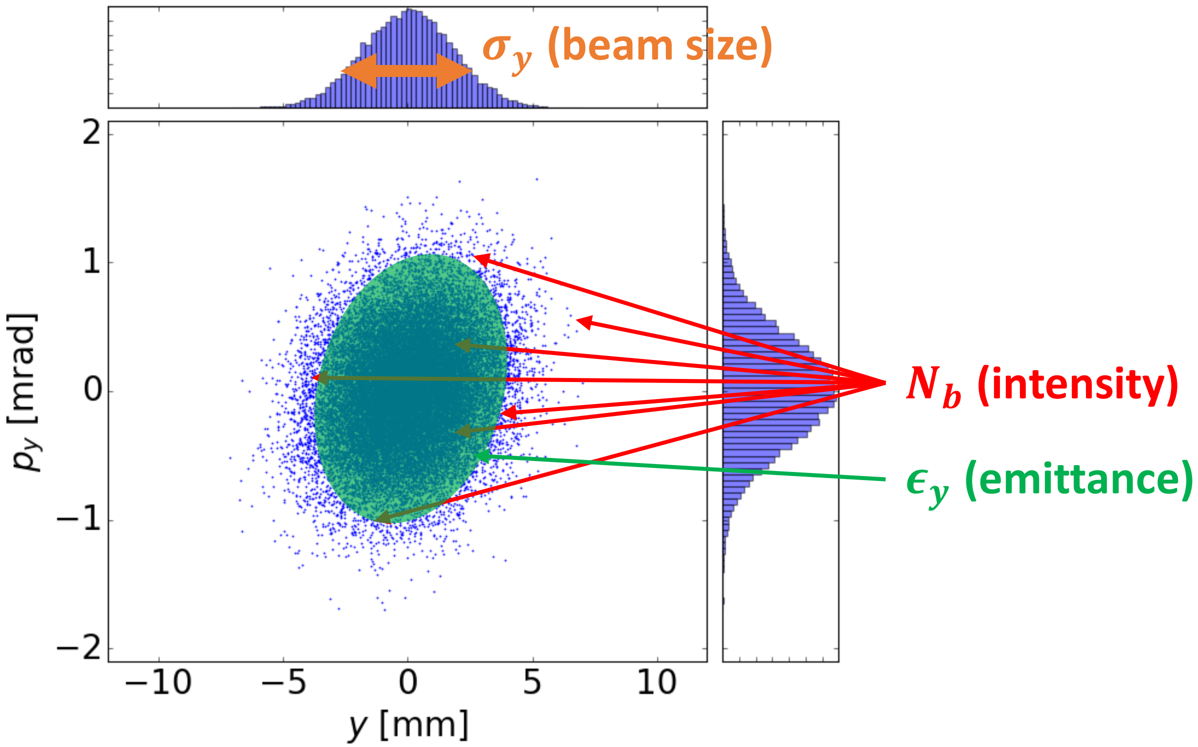


First fundamental task: **preserving beam properties** (intensity and emittance) during H^- injection.

Preserving beam properties

Beam properties

Statistical properties of incoming ensemble of particles



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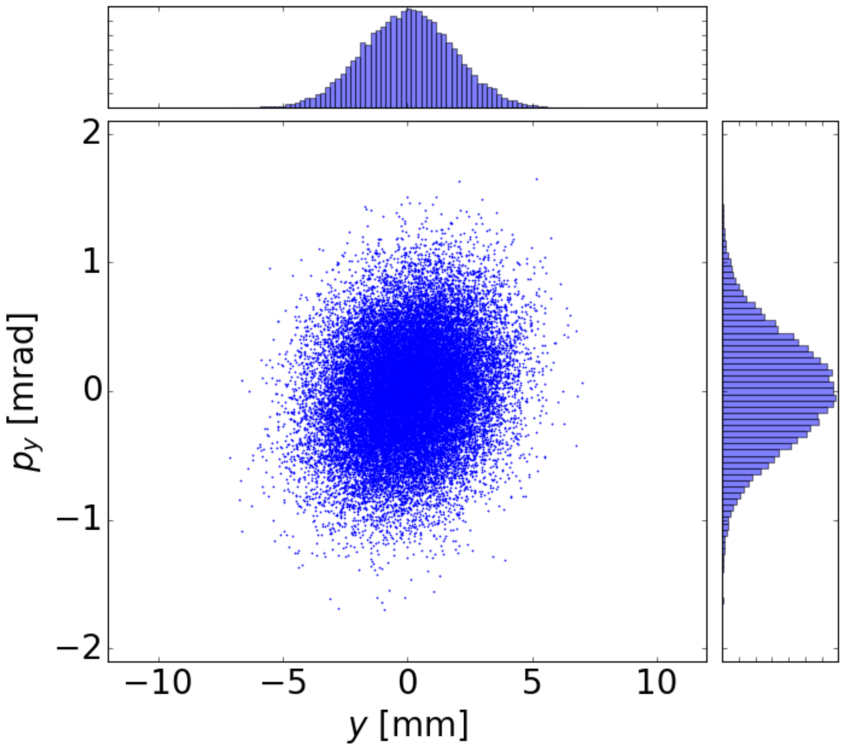
Preserving beam properties

Beam properties

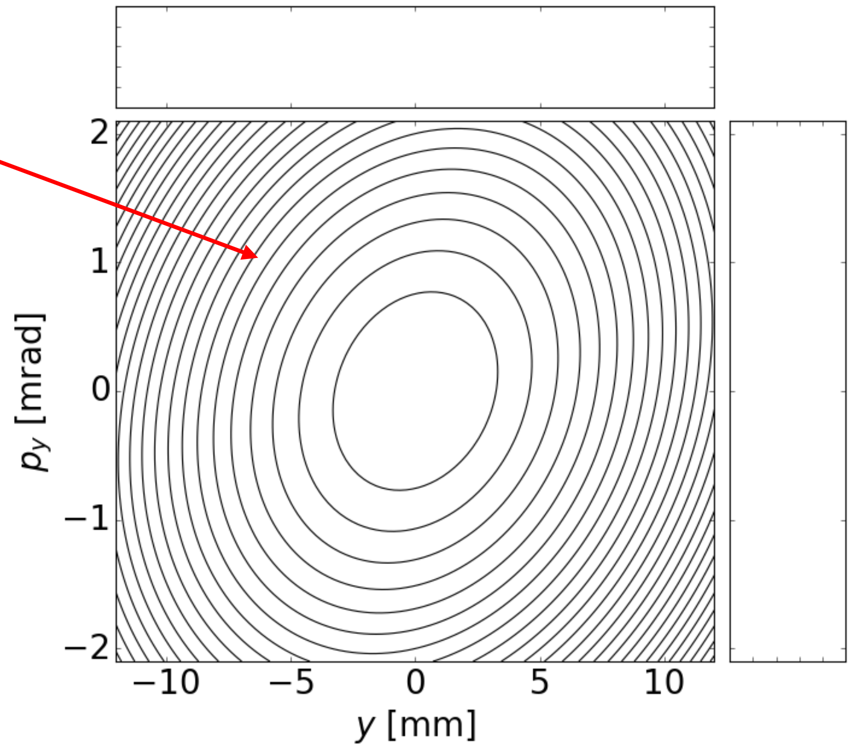
Statistical properties of incoming ensemble of particles



Machine properties

Magnets configuration (known also as **machine optics**)

Shape and orienatation of phase space lines



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Preserving beam properties

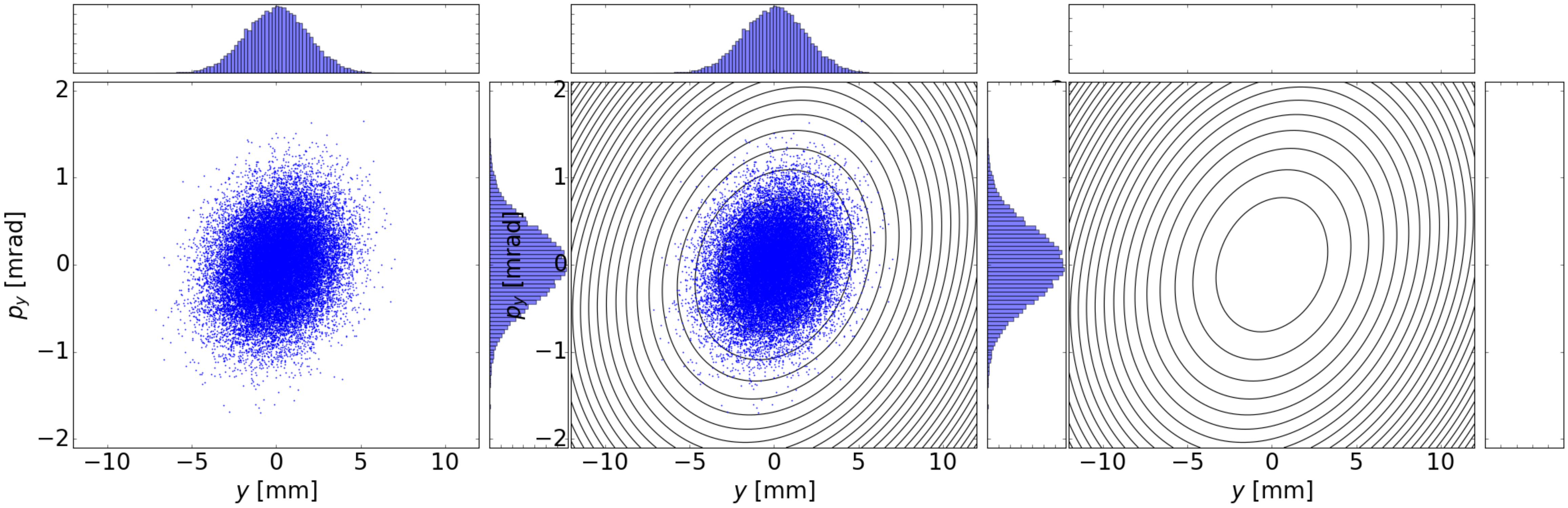
Matched

Beam properties

Statistical properties of incoming ensemble of particles

Machine properties

Magnets configuration (known also as **machine optics**)



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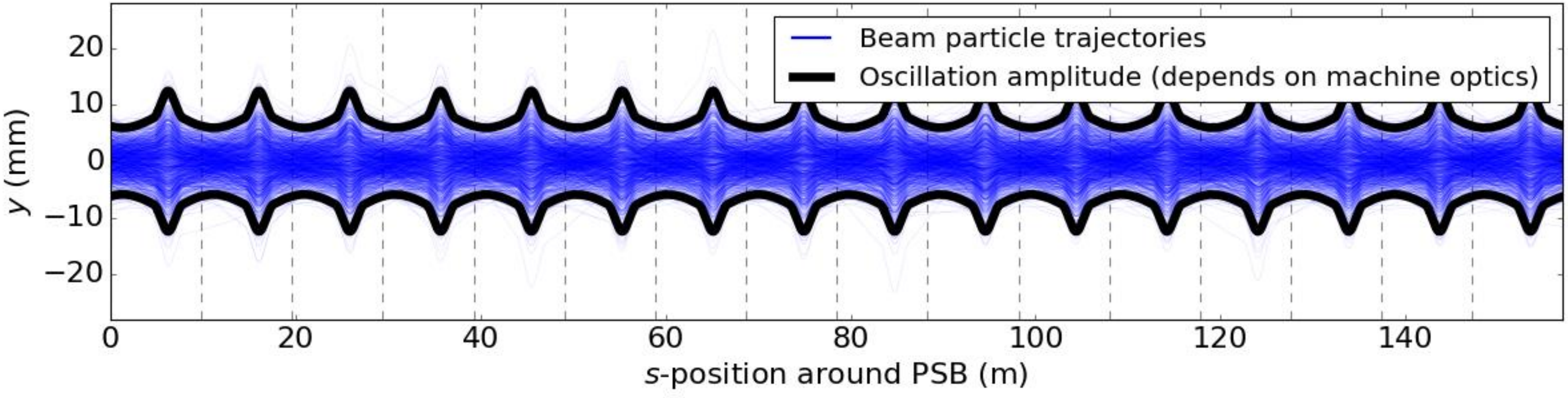
Preserving beam properties

Statistical properties of incoming ensemble of particles

Magnets configuration (known also as **machine optics**)



Particles perform transverse oscillations (**betatron oscillations**) as they circulate accelerator.

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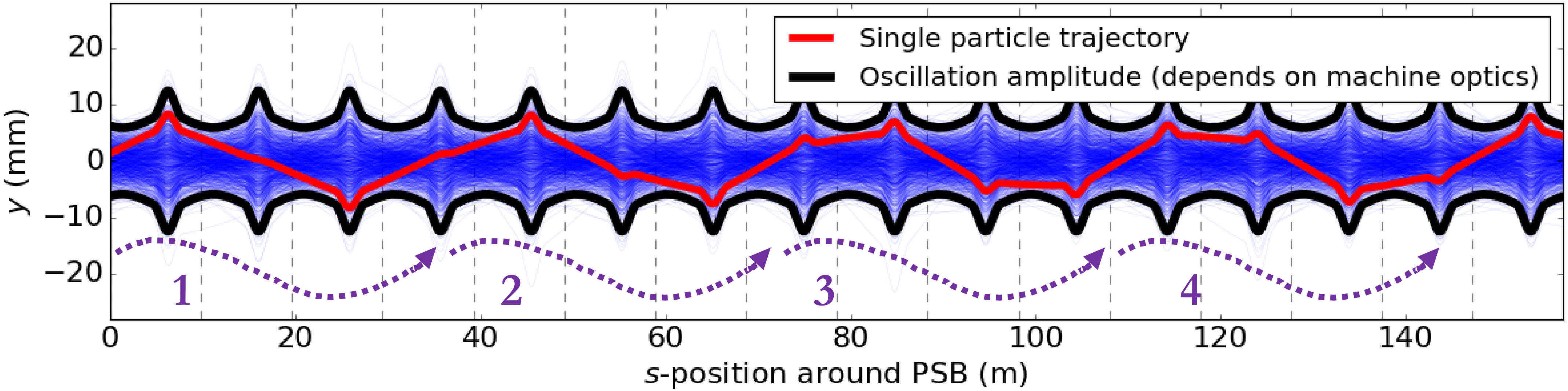
Betatron oscillations

During betatron oscillations, number (**intensity**) and density (**emittance**) of particles is preserved.



Betatron tune: number of oscillations per turn (here $Q_y = 4.45$).

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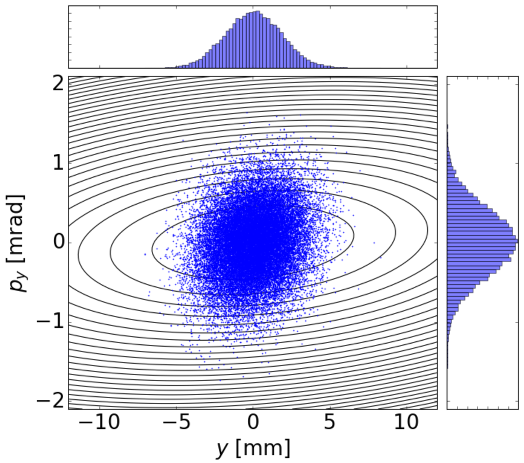
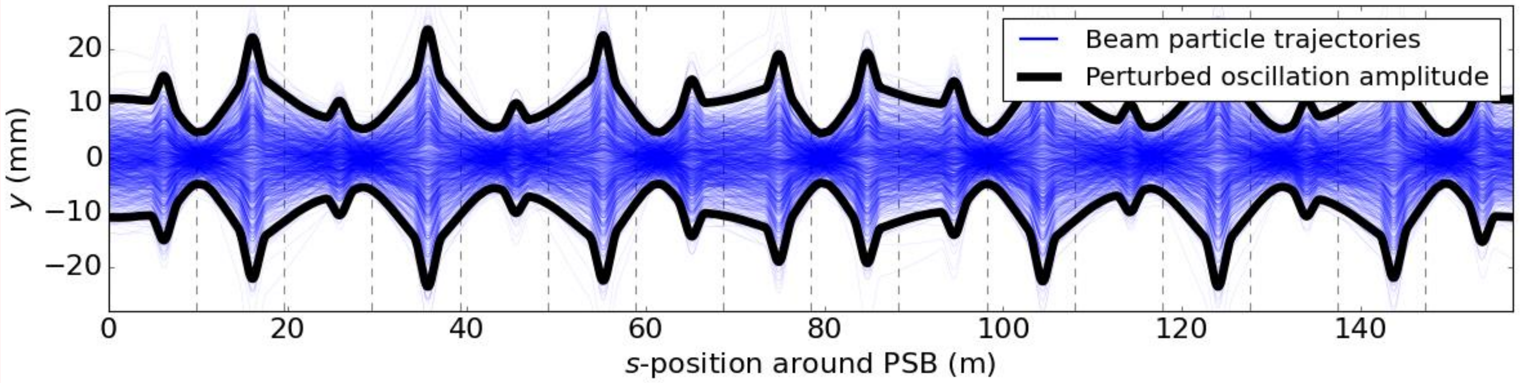
Injection perturbations

Injection bump induces fields errors → **perturbs machine properties**.

Mismatch



Larger oscillations



Perturbation increases oscillation amplitude→ **emittance growth** and **losses**.

During bump decay, perturbations **dynamically change**!

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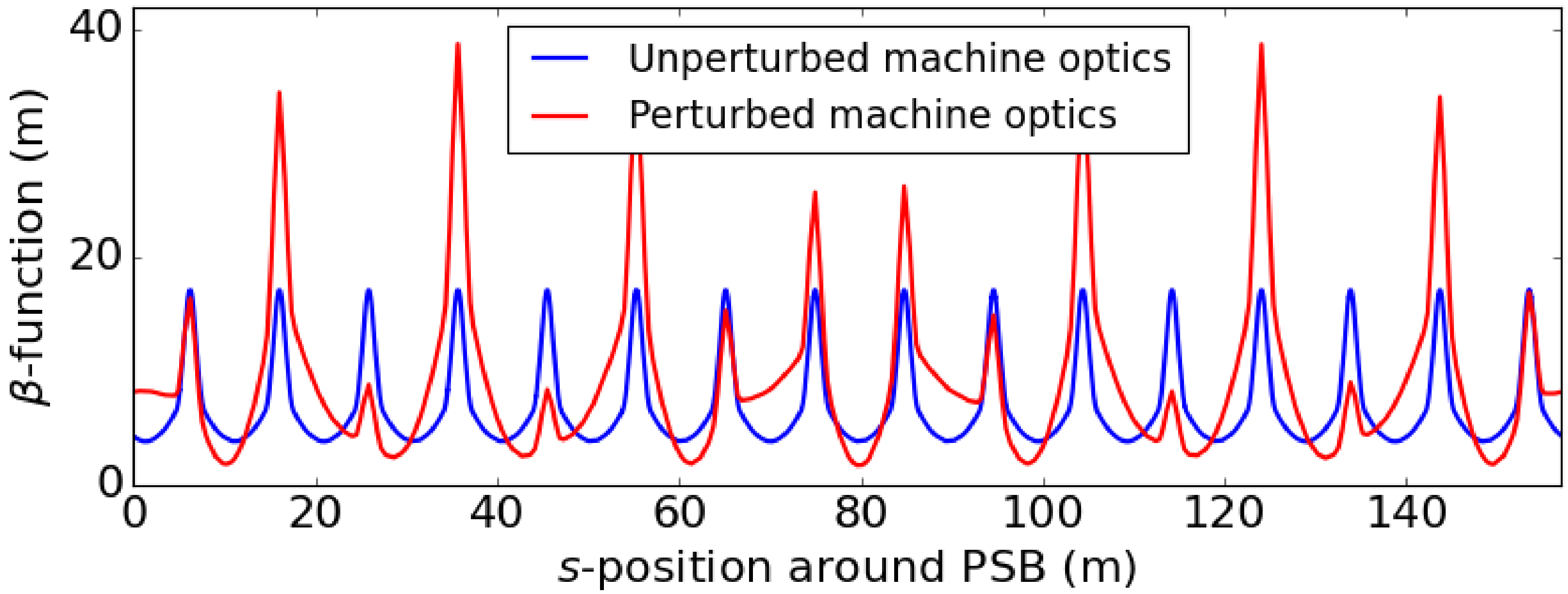
β-beating

Oscillation amplitude $\propto \sqrt{\beta}$
β-function defined by machine optics



$$\beta\text{-beating} = \frac{\delta\beta}{\beta} \times 100\ (\%)$$

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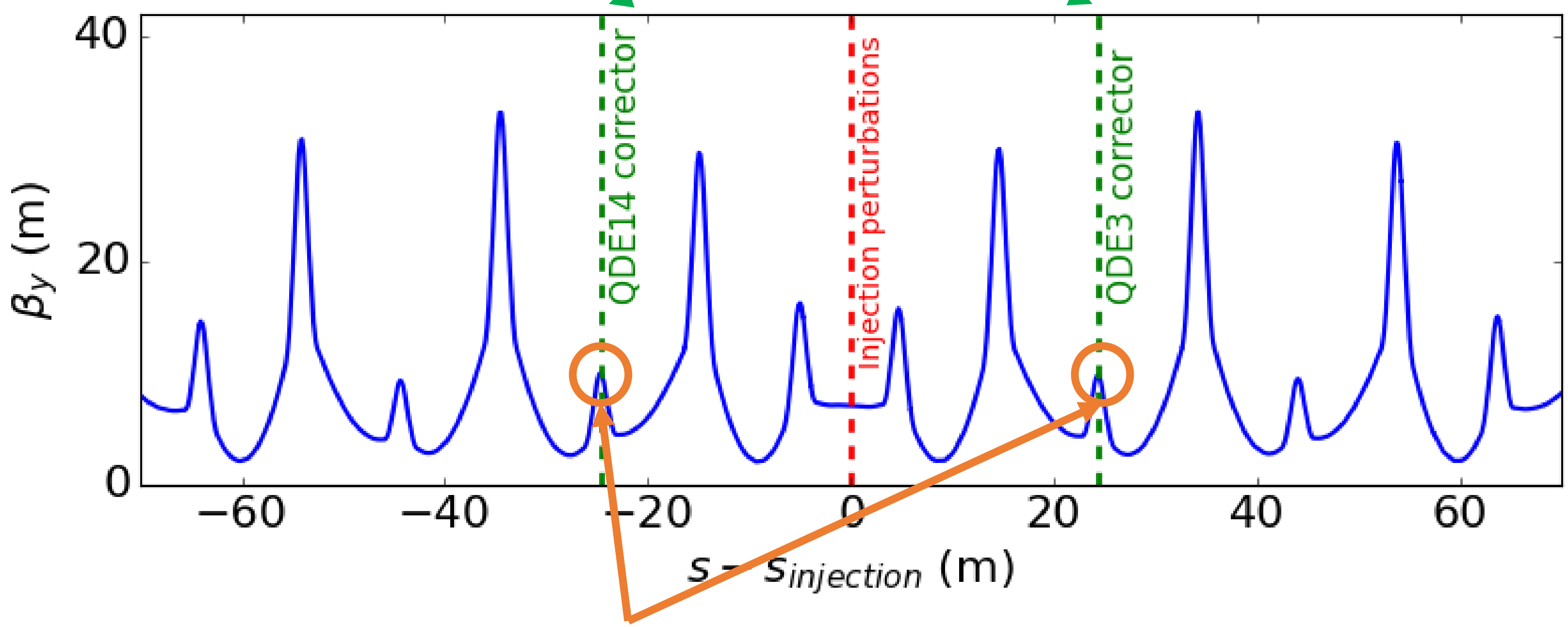
Method of measurement & correction

Devise method from **theoretical** understanding.

Modify PSB properties to dynamically compensate β-beating.

Identify local quadrupole corrector magnets



Calculation of dynamic β-beating correction ← Interpolation to pre-defined response matrix ← Local β-beating measurement with k-modulation

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Method of measurement & correction

Devise method from **theoretical** understanding.

Modify PSB properties to dynamically compensate β-beating.

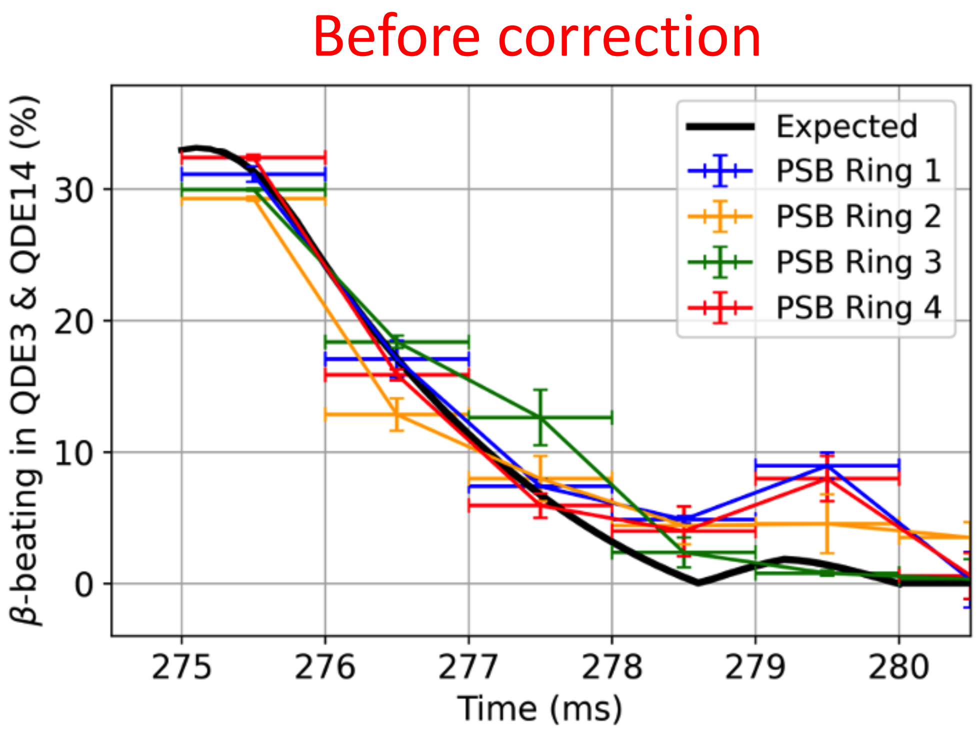
Simulation model to validate and test method.

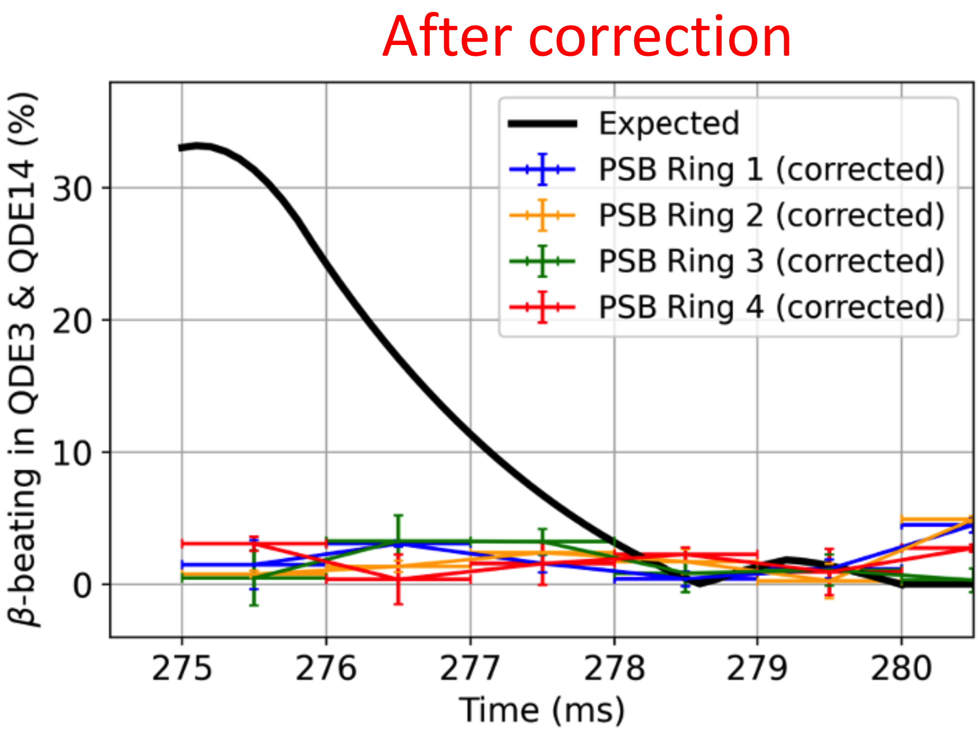
Computationally reproduce realistic machine conditions.

Apply in accelerator and see **experimental** effects.

Operational implementation.

Experimental results





Fast and dynamic β-beating correction from $> \mathbf{30\%}$ **to** $< \mathbf{3\%}$.

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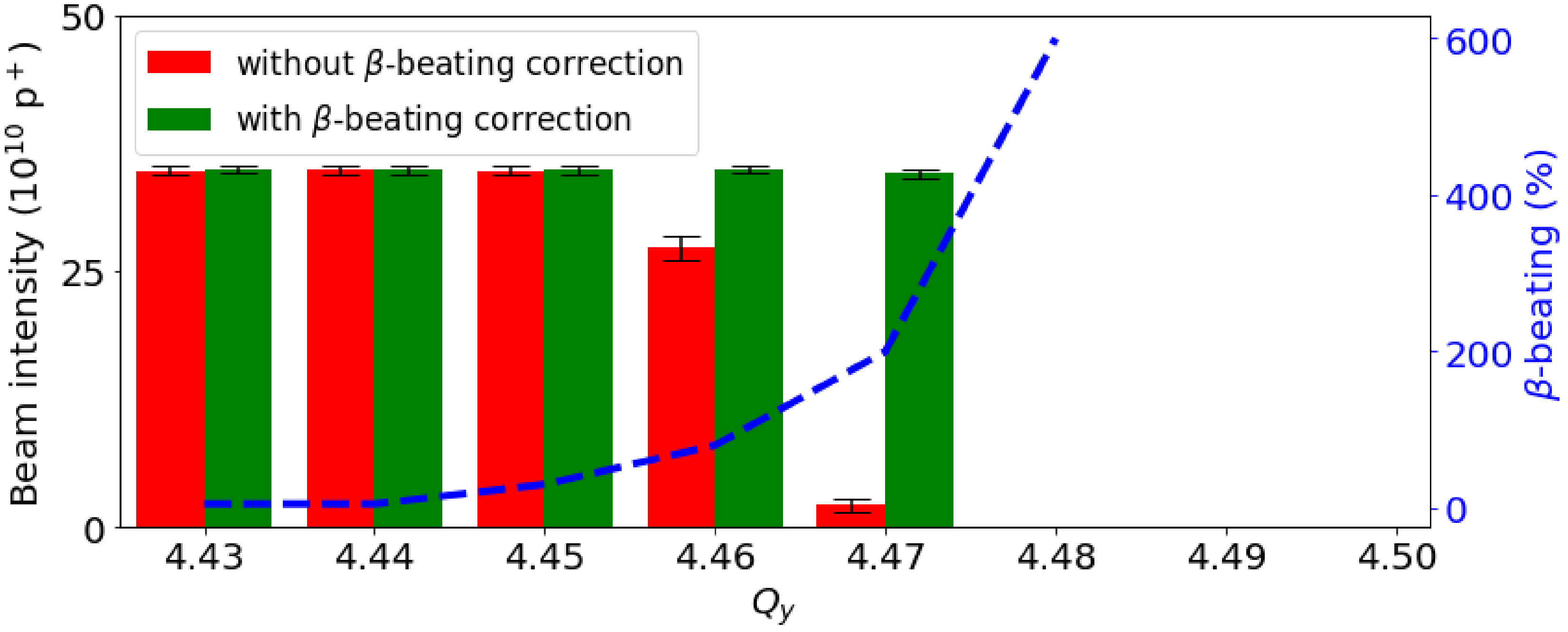
Experimental results

Strength of perturbation strongly depends on **betatron tunes** Q_x, Q_y.



$\boldsymbol{\beta}$-beating correction restores intensity and emittance at high tunes.

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Beam evolution after injection

Field errors (like ones of injection) **common** in circular accelerators: perturb machine properties.

Injection effects take only 1% of PSB time (5/530 milliseconds)!

In “longer” beam storage, **space charge** effects become important!

Second fundamental task: **maintaining** beam properties throughout full PSB cycle.

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Resonances

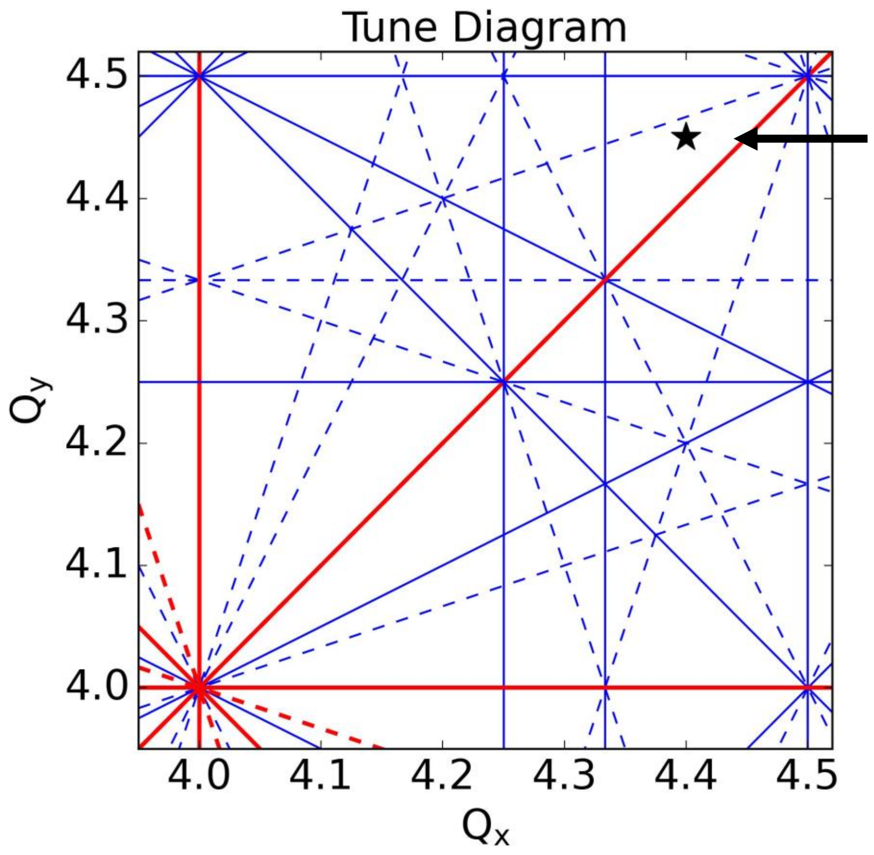
Magnetic field errors seen periodically by the beam turn-by-turn.

- If **betatron tune Q** close to excited resonance→ **resonant motion**.

Resonance condition:

$$\boldsymbol{mQ_x + nQ_y = p}$$
$$\boldsymbol{m, n, p} \in \mathbb{Z}$$

Resonances plotted as lines in the tune diagram → (Q_x, Q_y) needs to be **far from these lines**.



(Q_x, Q_y): nr. of oscillations in x and y

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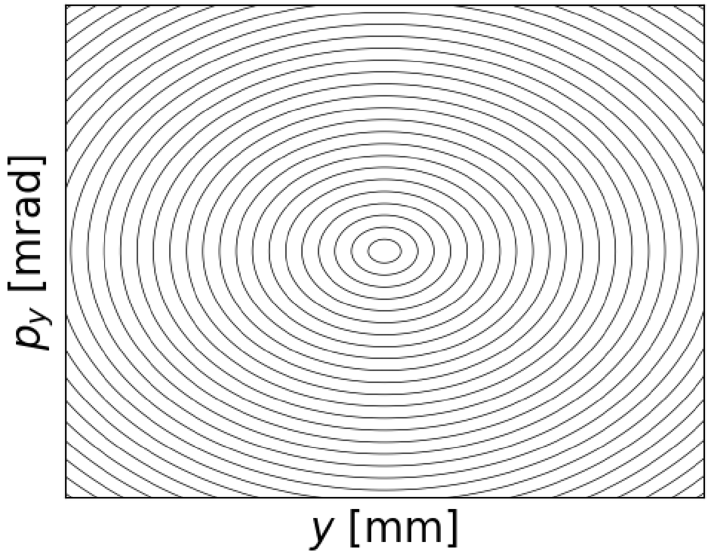
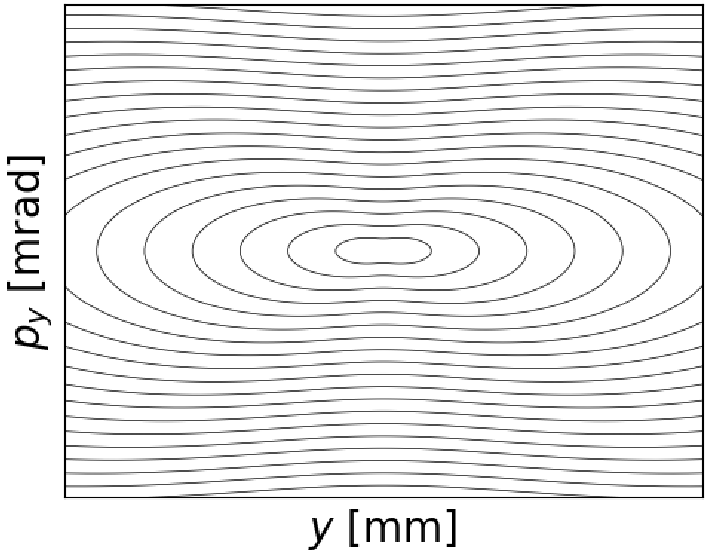
Resonances

Motion near resonance is perturbed and can become unstable.

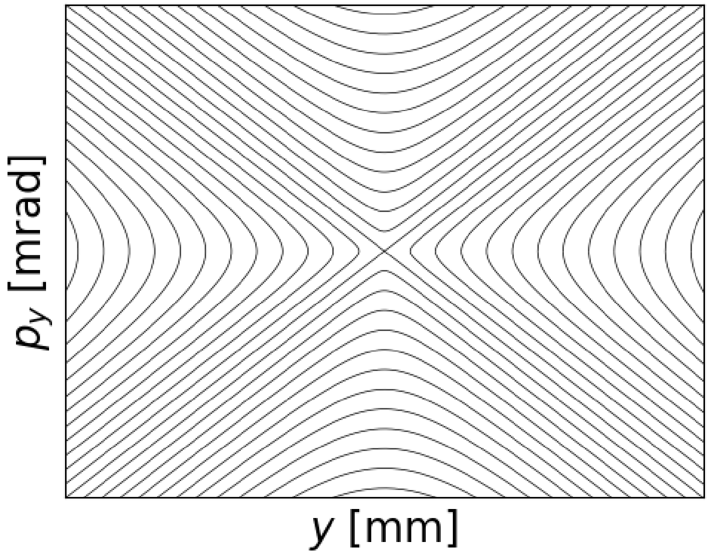
Far from resonance:
stable



Near resonance:
perturbed



On resonance:
unstable



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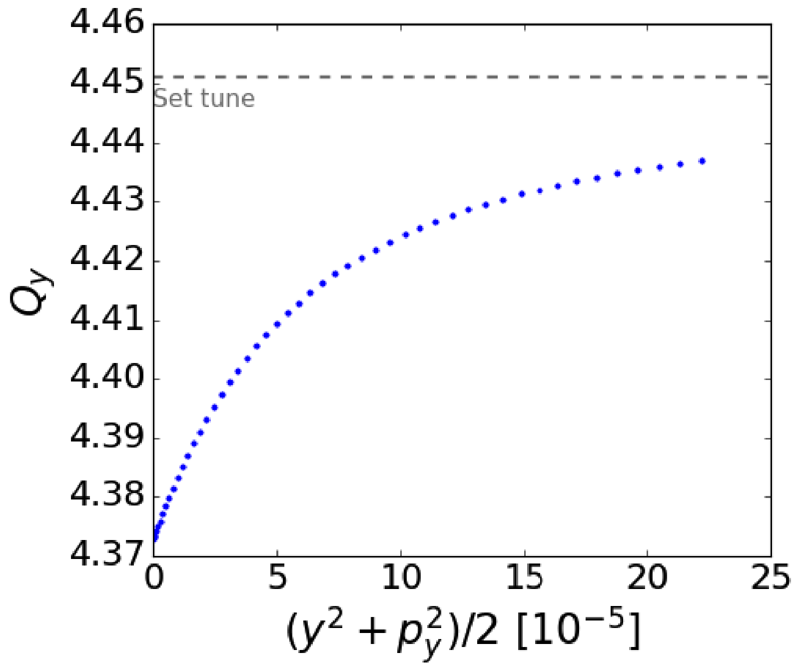
Space charge

Space charge induces **non-linear force** that **defocuses** particles depending on their **transverse location** from the center.

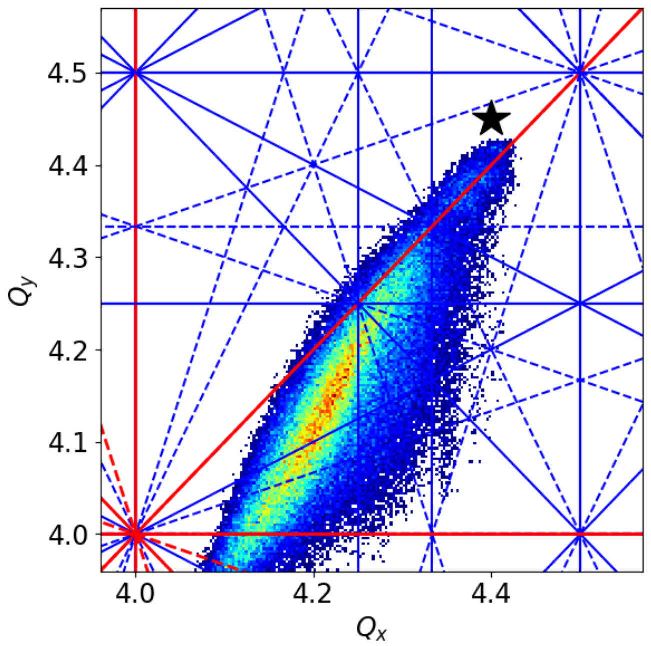
Defocusing induces an **amplitude detuning**.

Space charge drives particles to resonances: **beam degradation**.

Amplitude detuning in 1D



Amplitude detuning in 2D



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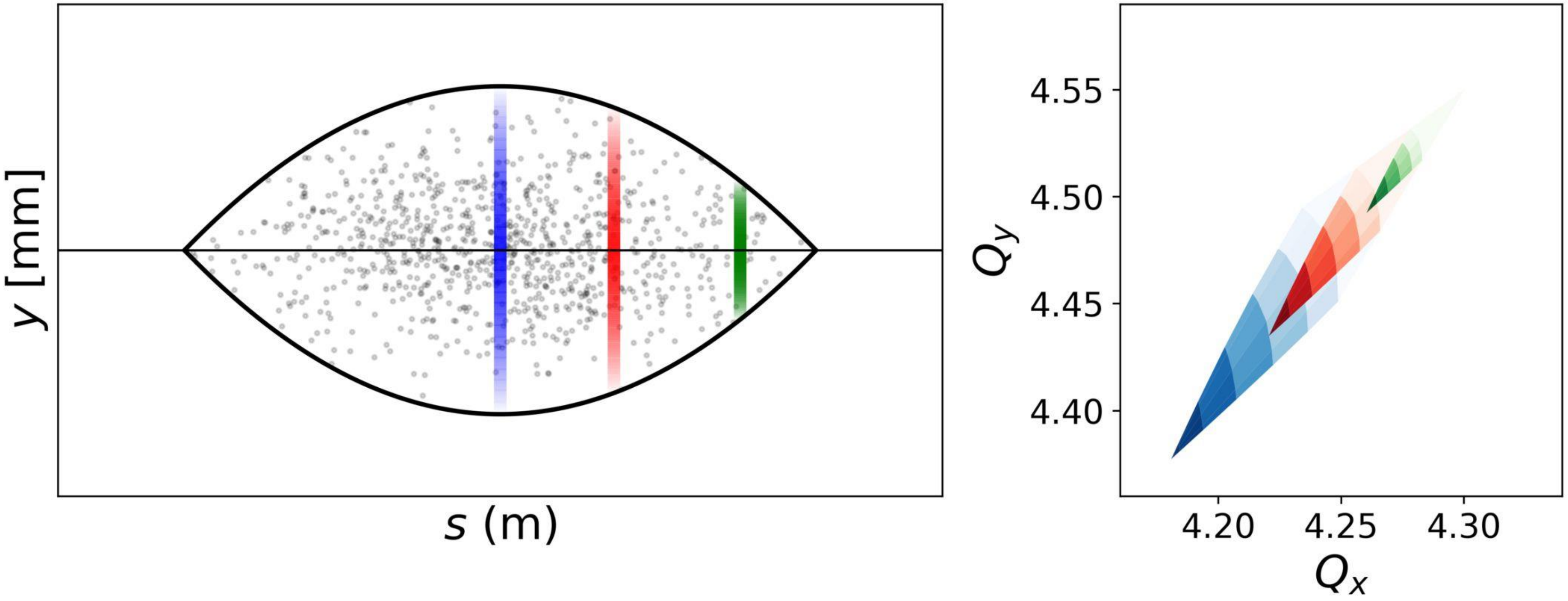
Beam degradation due to space charge

In bunched beams, the maximum tune spread depends on the local line density.

- **large** line density: **larger** tune spread
- **smaller** line density: **smaller** tune spread
- **near the tail** of the bunch, the tune spread is **very small**



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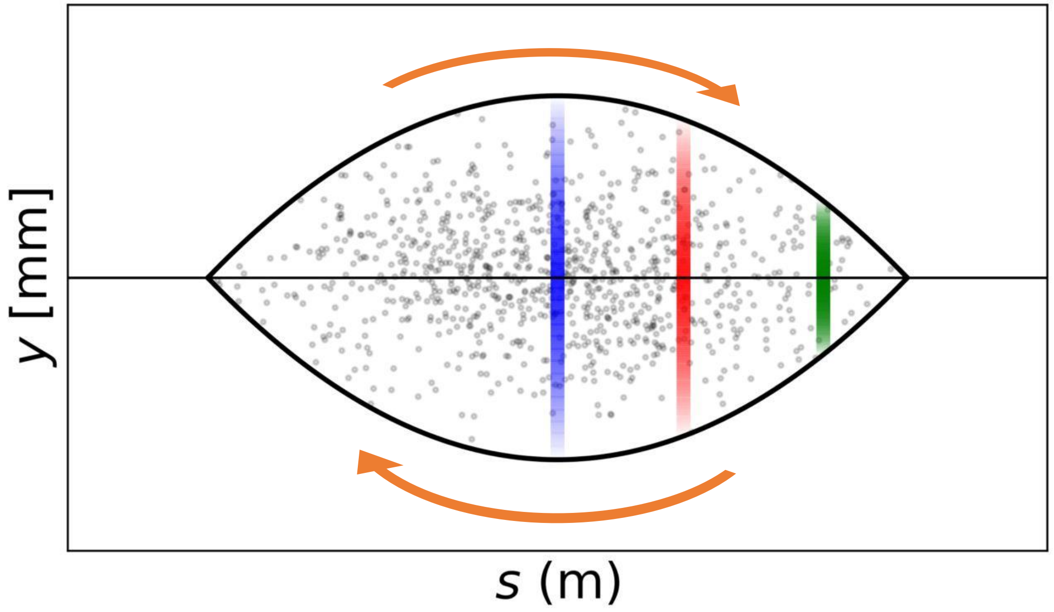
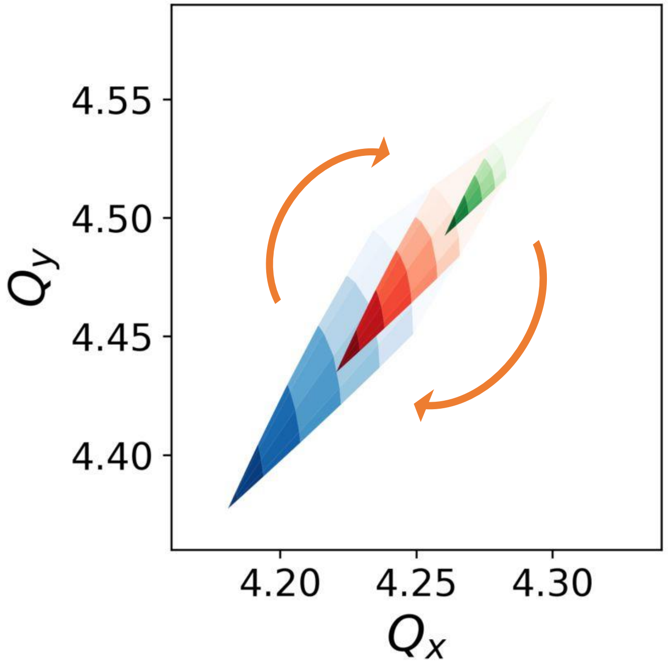
Beam degradation due to space charge

Particles oscillate also in longitudinal plane (synchrotron oscillations).

Local line density of a particle changes → **tune modulation**.





Tune modulation leads to **periodic resonance crossing**: particles drift outwards.

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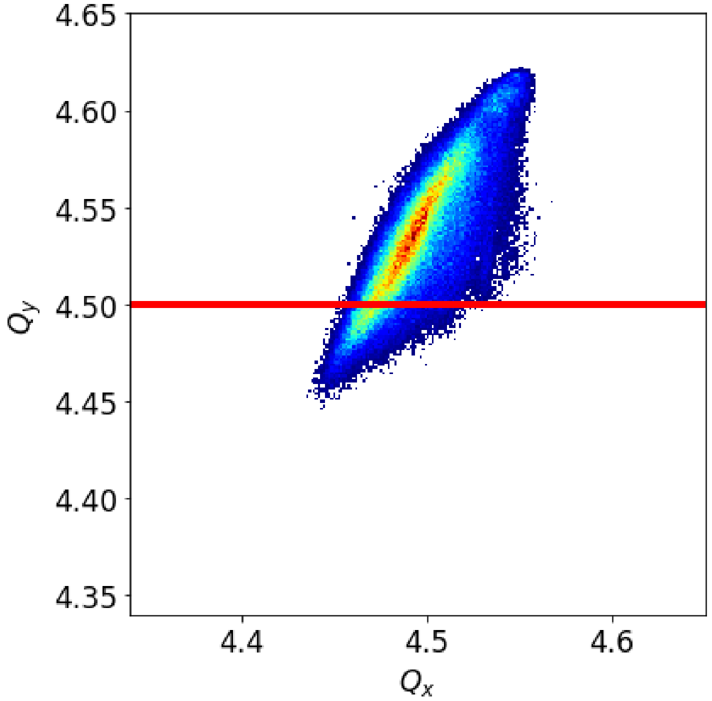
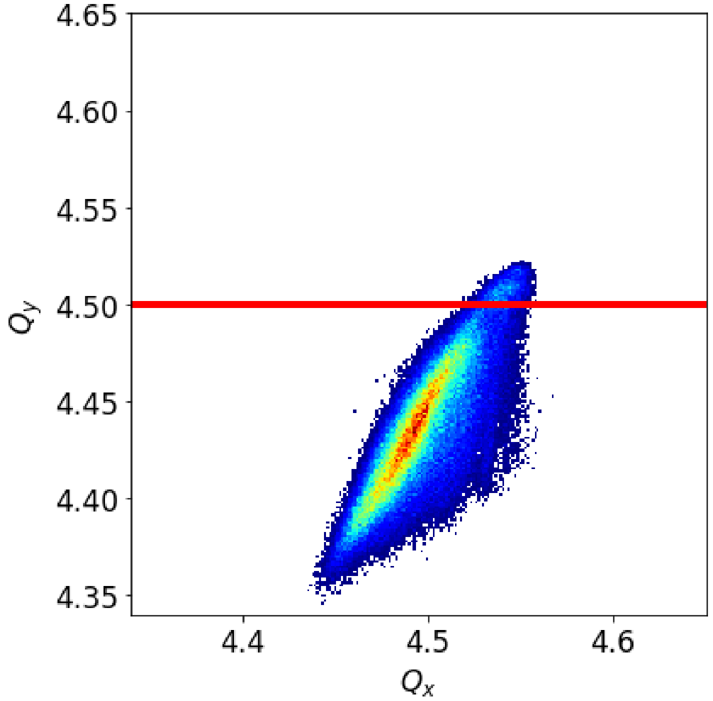
Beam degradation due to space charge

Low amplitude particles (beam core) interact with the resonance: **emittance growth**



High amplitude particles (beam tails) interact with the resonance: **losses**



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Optimizations along PSB cycle

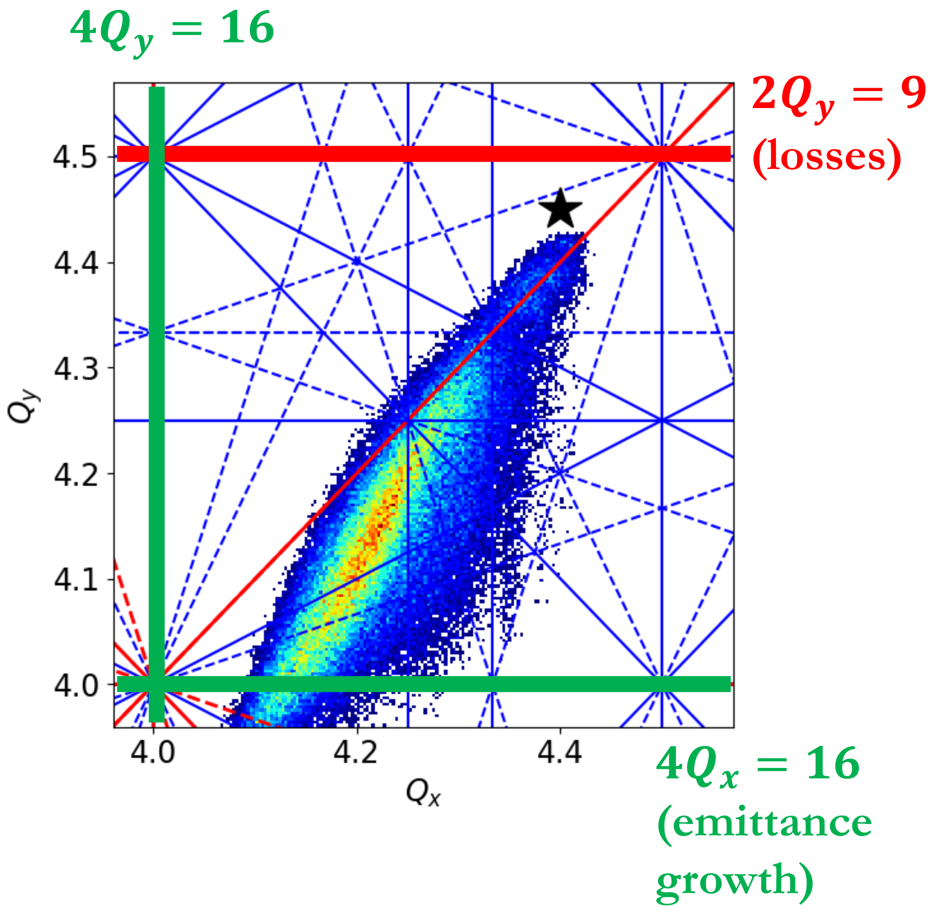
Correct injection perturbations

Dynamically correct induced β-beating.

Minimize beam degradation due to space charge

Adjust tunes evolution

Correct resonances (similar mechanisms that control β-beating)



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Optimizations along PSB cycle

Correct injection perturbations

Dynamically correct induced β-beating.

Minimize beam degradation due to space charge

Adjust tunes evolution

Correct resonances (similar mechanisms that control β-beating)

Apply optimal settings to machine

Impact on brightness performance.

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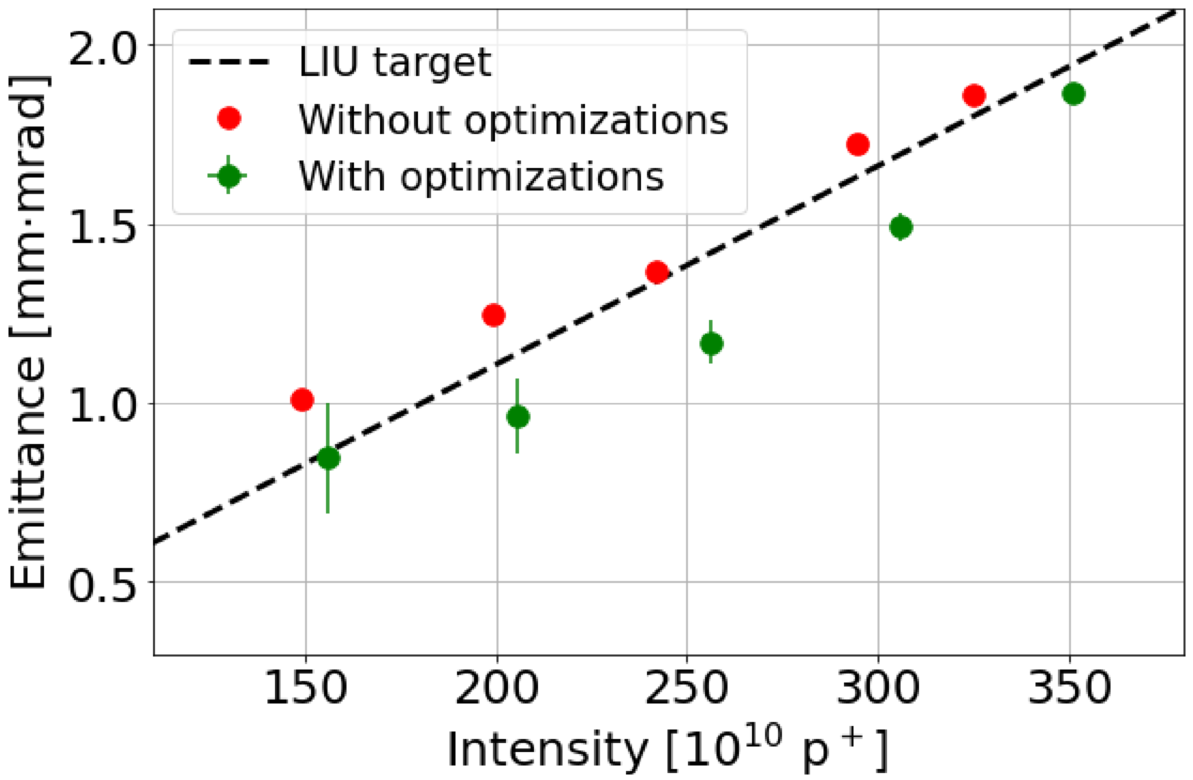
Experimental results



Brightness increase **beyond LIU targets**!

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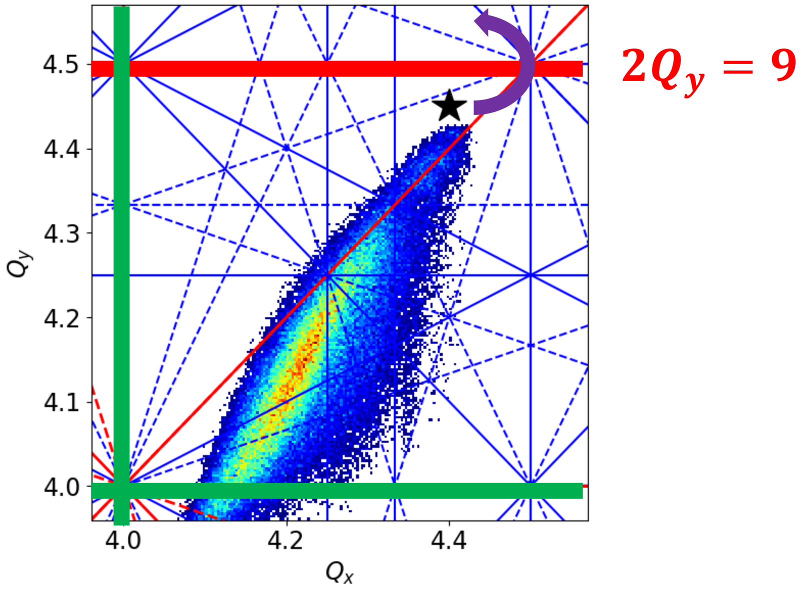
Pushing the limit of PSB

So far: PSB optimized for operation with **maximum brightness** performance.

Now: explore limits of PSB by injecting above half-integer resonance.

Needs **understanding** of half-integer resonance effects in combination with space charge.



Third fundamental task: **study space charge** effects near the half-integer resonance.

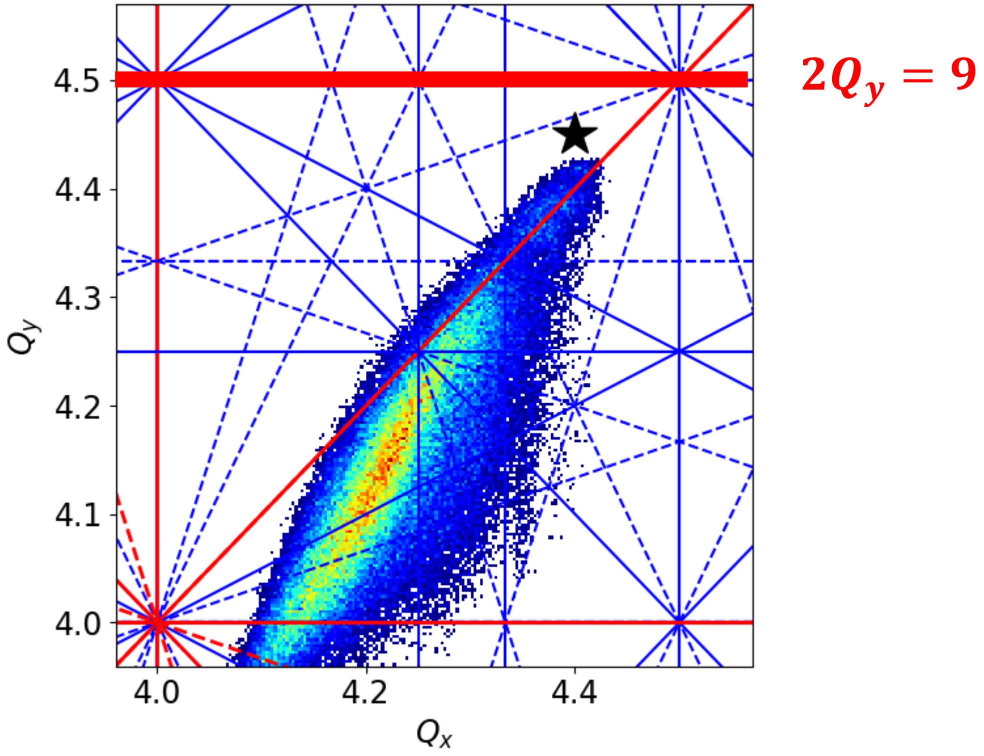
Half-integer resonance

Why half-integer resonance:

1. Present in all circular accelerators
2. Strong and difficult to control
3. Bottleneck for most strong space charge machines (including PSB)

What was achieved in PSB:

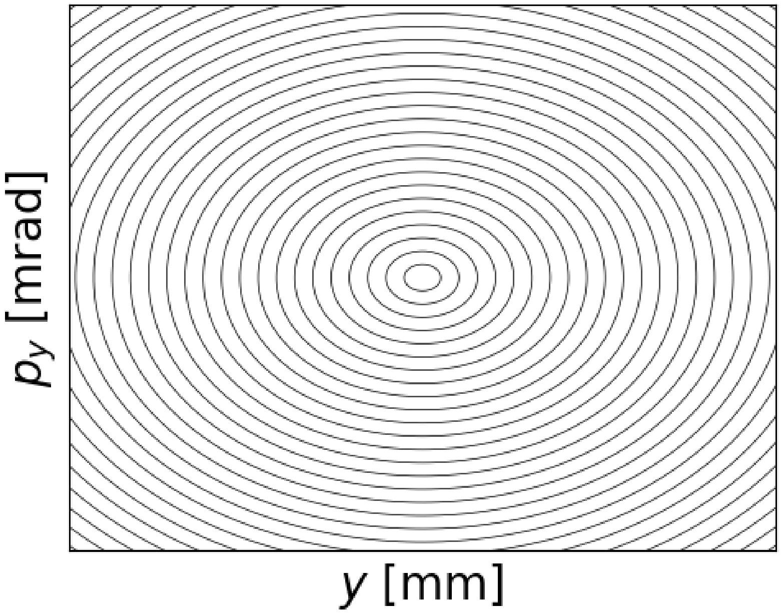
1. Excellent **compensation**
   using improved techniques
2. Controlled **excitation**
   by deliberately degrading compensation
3. Experimental **measurement**
   by characterizing unstable region



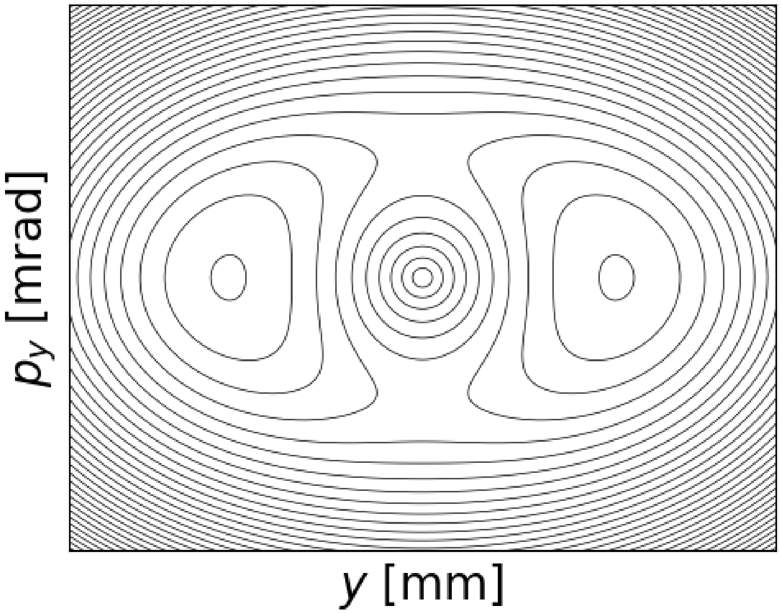
Non-linear phase space topologies

Non-linearities (like **space charge**) create more complicated phase space structures near resonances.

Linear phase space



Non-linear phase space



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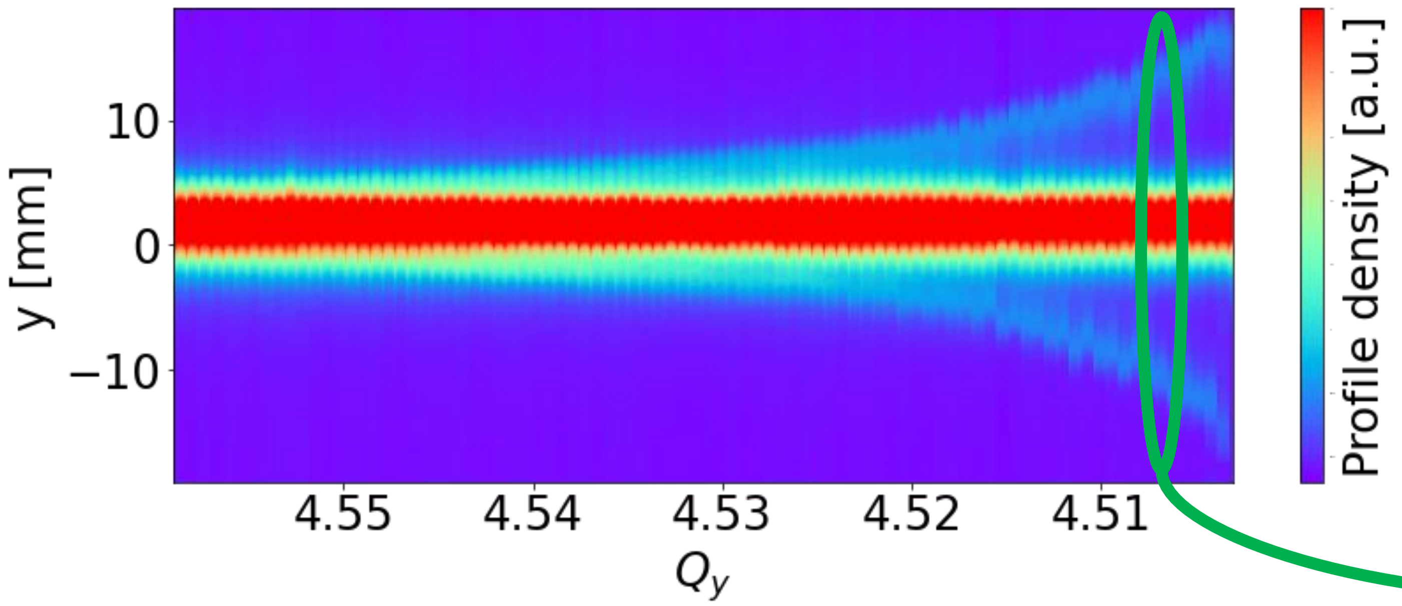
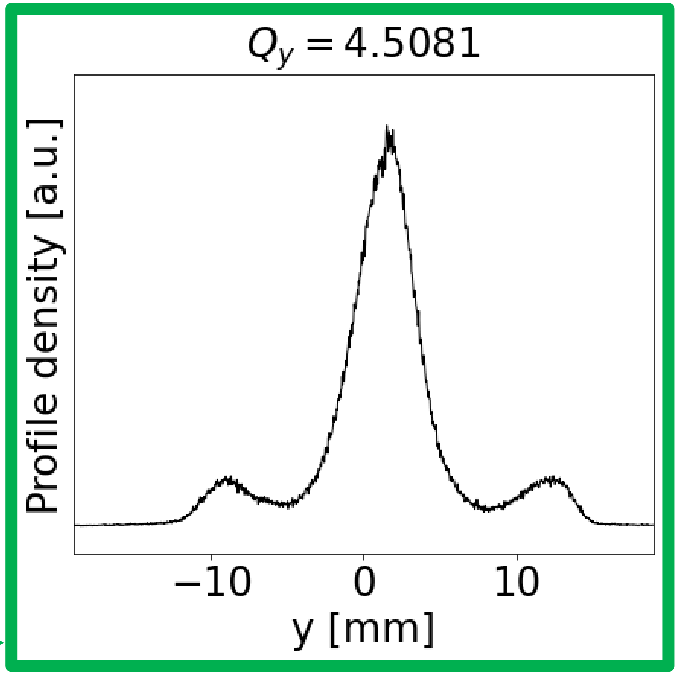
Experimental results

Adiabatic transition from linear to non-linear phase space.





Measurement of **trapping** in half-integer resonance due to space charge!

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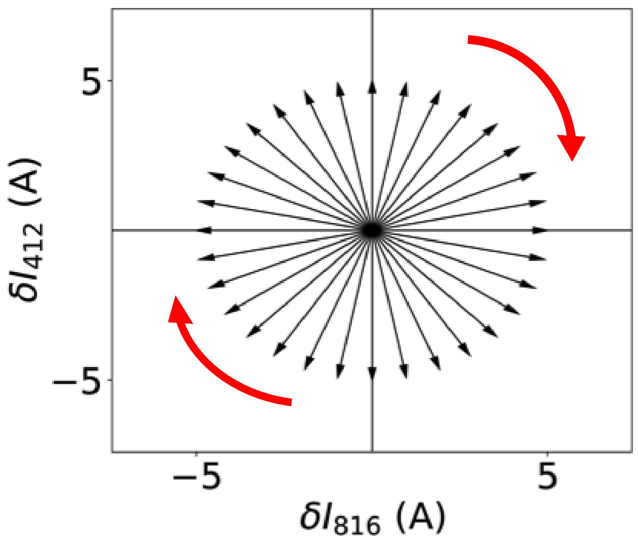
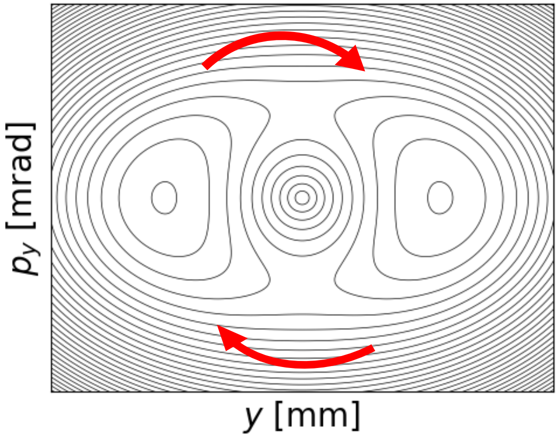
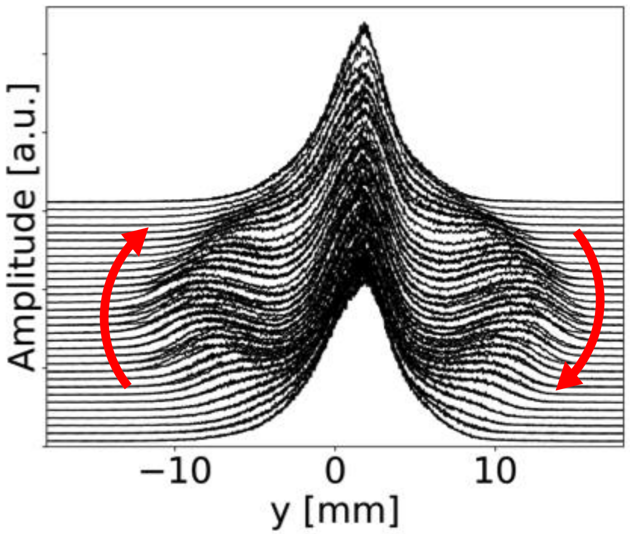
Experimental results

Controlling the phase space distribution by means of resonance excitation.







Characterization of space charge effects near half-integer resonance.

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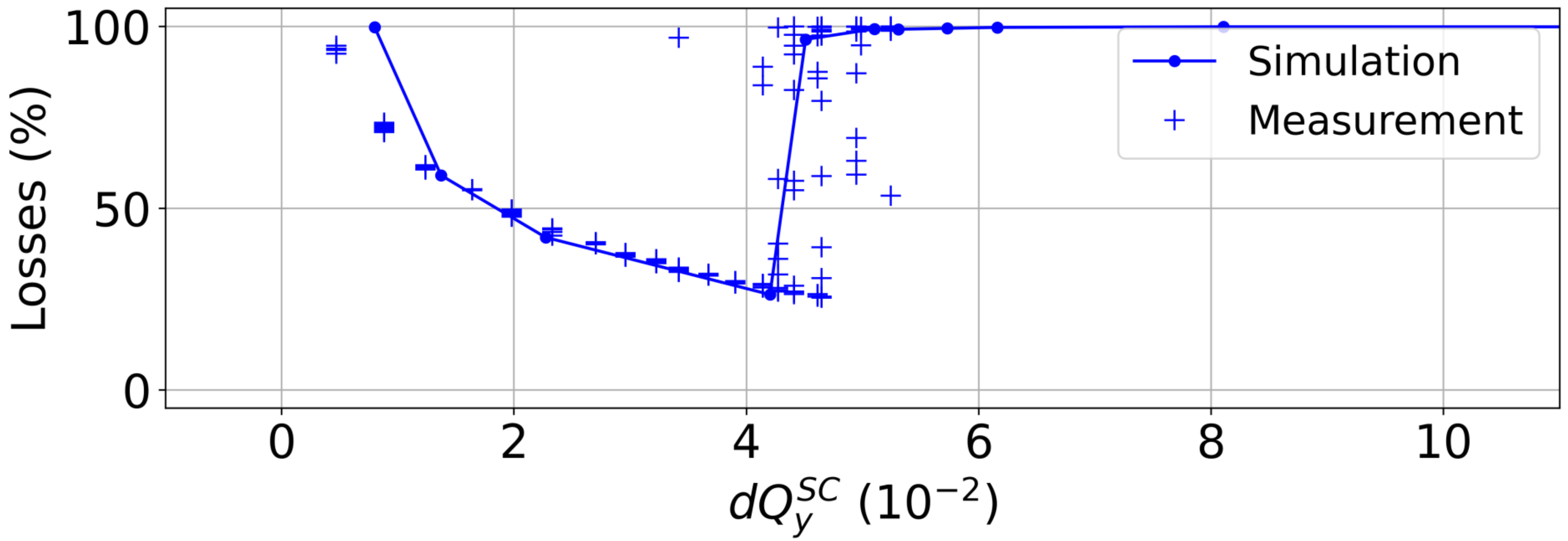
Benchmarking simulation models

Beam losses vs. space charge when crossing half-integer resonance.



Excellent **agreement** of measurements and tracking simulations.

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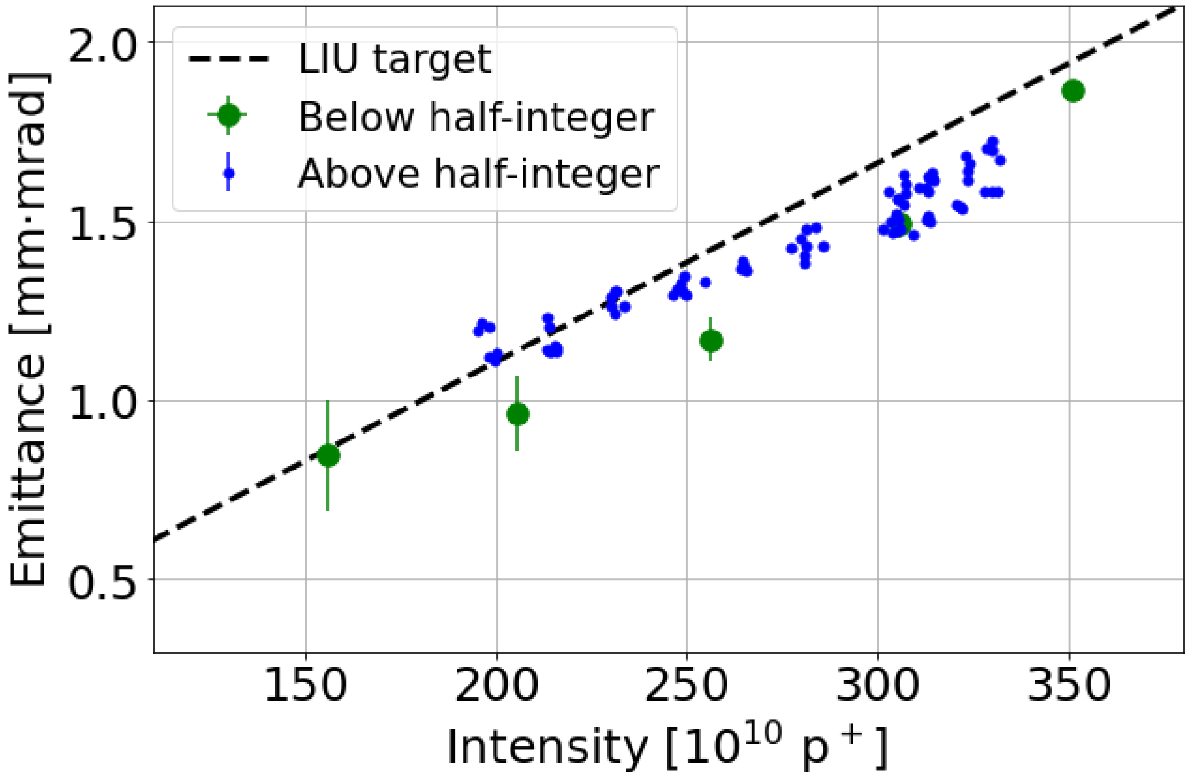
Beam brightness

The understanding & minimization of unwanted half-integer effects lead to the:



Feasibility of half-integer crossing with beyond LIU brightness!

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Conclusions

PSB received upgrades within LIU to improve brightness performance.

Injection perturbations identified, measured and corrected and beam parameters optimized in PSB:
Contributed to beam brightness increase beyond LIU targets.

Space charge effects near half-integer resonance characterized experimentally for the first time:
Improved understanding and modelling of beam dynamics.

Optimized high-brightness beam performance and explored accelerator's capabilities.

Thank you for your attention!

This work has been accomplished with the valuable contributions and assistance of:

S. Albright, F. Antoniou, F. Asvesta, H. Bartosik, C. Bracco, A. Calia, G. Franchetti,
G.P. Di Giovanni, D. Gamba, S. Kostoglou, T. Levens, K. Li, E. H. Maclean,
K. Paraschou, E. Renner, F. Roncarolo, G. Rumolo, P. Skowronski, G. Sterbini, PSB OP team

Supporting Material

References

[1]: T. Prebibaj et al., Injection Chicane Beta-Beating Correction for Enhancing the Brightness of the CERN PSB Beams, HB2021 (MOP18).
[2]: T. Prebibaj et al., “Beta-beat correction in the PSB during injection bump decay”, Presentation at ABP Injectors Working Group Meeting, CERN, Apr. 2020 [Online].
[3]: T. Prebibaj et al., “Status of the k-modulation application”, Presentation at Injectors Performance Panel Meeting, CERN, Geneva, Switzerland, Nov. 2020 [Online].

[4]: K-Modulation Application, Accelerating Python Q4 2020 Meeting (link).

[5]: T.Prebibaj et.al., Studies on the Vertical Half-Integer Resonance in the CERN PS Booster, IPAC22, June 2022 (MOPOST058).
[6]: PSB Half-Integer experiment, Space Charge WG Meeting 16/12/2021 (link)
[7]: Effects of Space Charge close to the Half-Integer Resonance in the PSB, INC Section Meeting 01/02/2022 (link).
[8]: Latest Space Charge Meeting

[9]: G. Franchetti and I. Hofmann, “Particle Trapping by Nonlinear Resonances and Space Charge”, in Nucl. Instr. and Meth. A 561, 2006, pp. 195-202.

[10]: T. Prebibaj et.al., Characterization of the Vertical Beam Tails in the CERN PS Booster, IPAC22, June 2022 (MOPOST057)
[11]: PSB profile observations: evolution along the cycle, Space Charge WG Meeting 22/04/2021 (link).
[12]: Wire scanner impact on the beam profile for the PSB, Space Charge WG Meeting 20/10/2021 (link).

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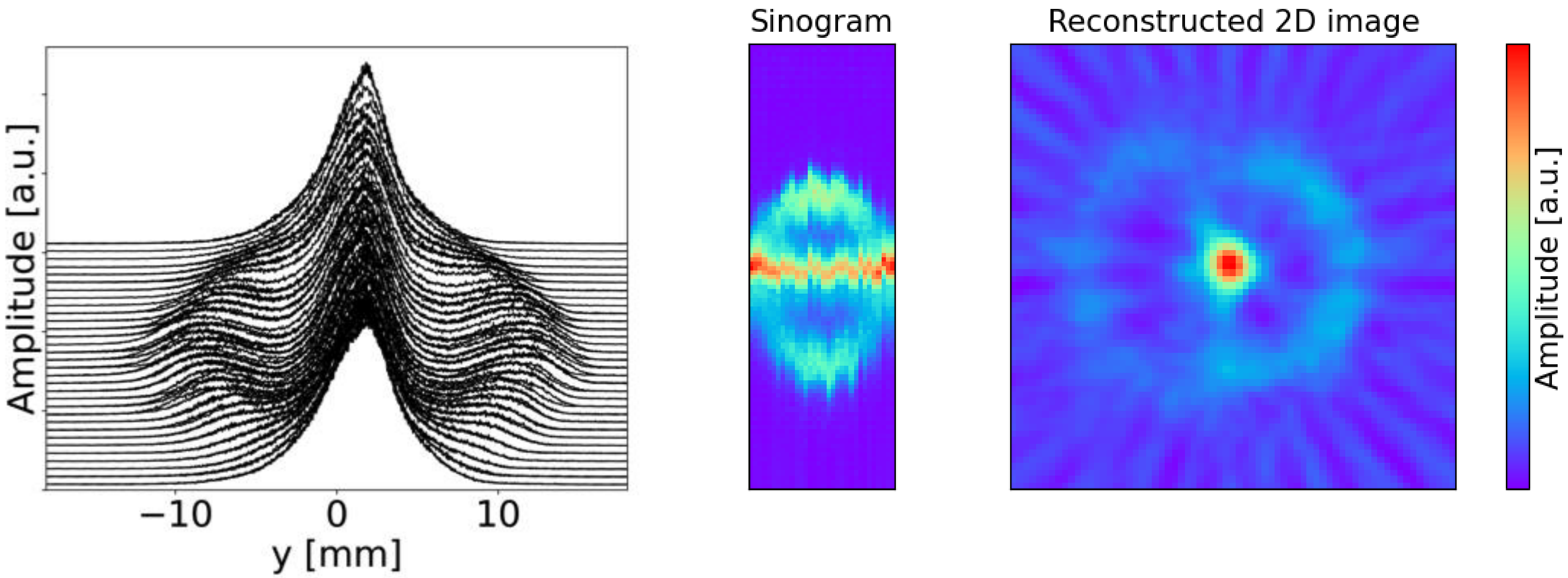
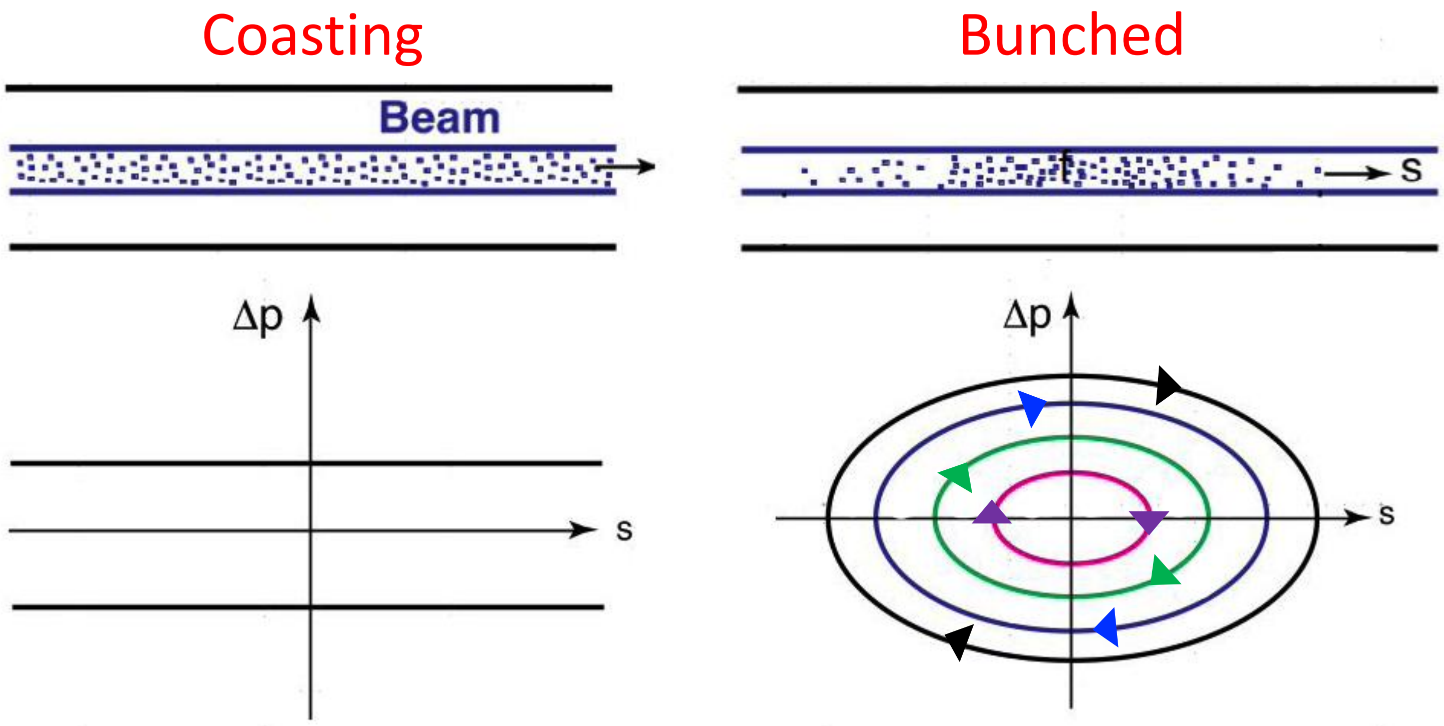
Tomography in the transverse plane



Longitudinal motion

- Realistic beams are not exactly monoenergetic: they have energy (momentum) spread $\mathbf{\Delta E}$ $(\mathbf{\Delta p})$.

- Different sets of longitudinal variables are used:
  $(z, \Delta E)$, $(\phi, \Delta E)$, $(\phi, \Delta p)$, …

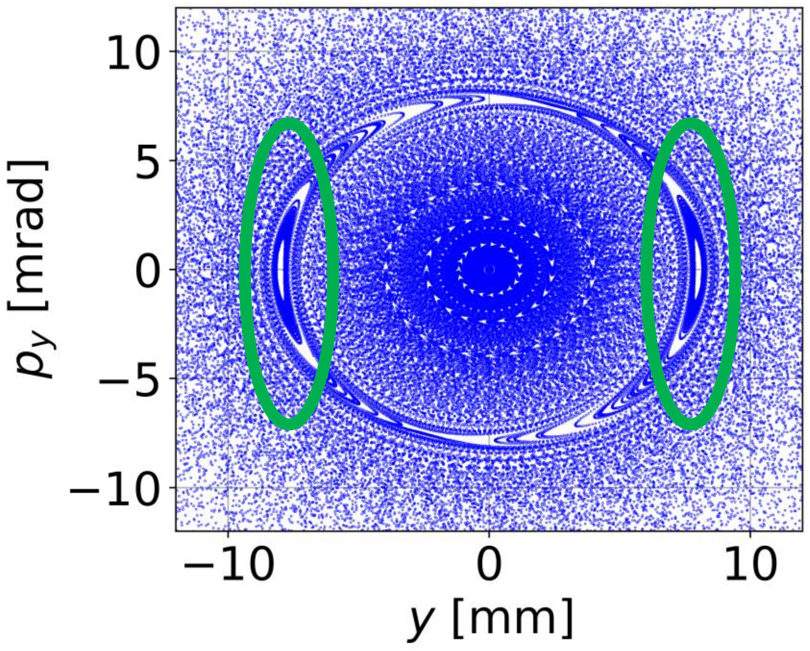


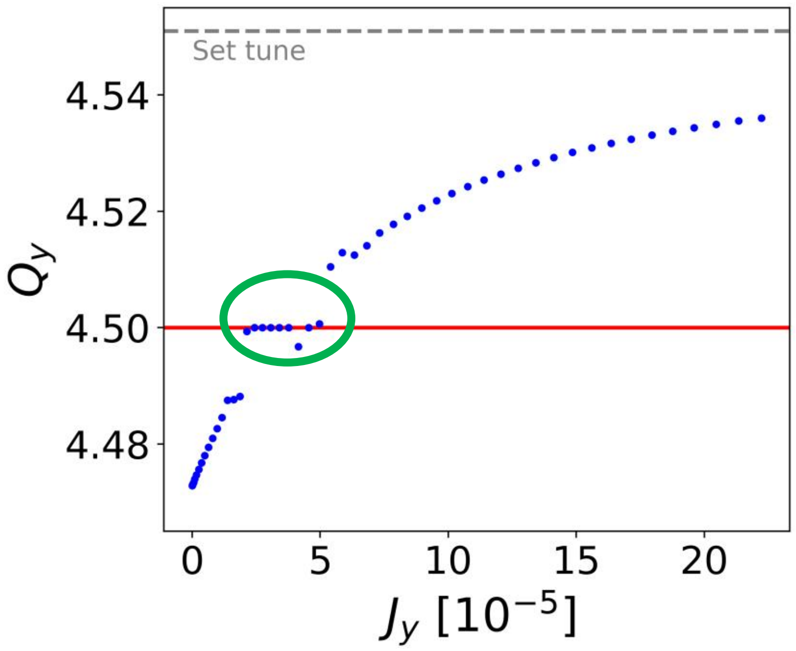
- Beams can be bunched or unbunched (coasting).

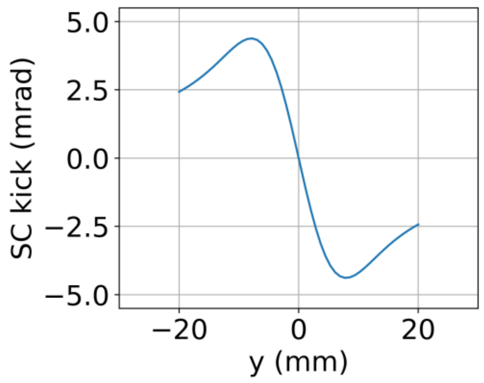
- Bunched beams perform synchrotron oscillations in the longitudinal phase space (energy-phase oscillations).

- Transverse motion can be coupled to the longitudinal motion:
  - Dispersion: orbit change with energy spread.
  - Chromaticity: tune change with energy spread.

Toy-model of 1-D resonance crossing







- 1-turn map + space charge kicks (amplitude detuning) + quadrupolar error (half-integer excitation).
- Appearance of stable resonance islands.
- The size of the islands depends on the excitation amplitude and the detuning gradient [9].

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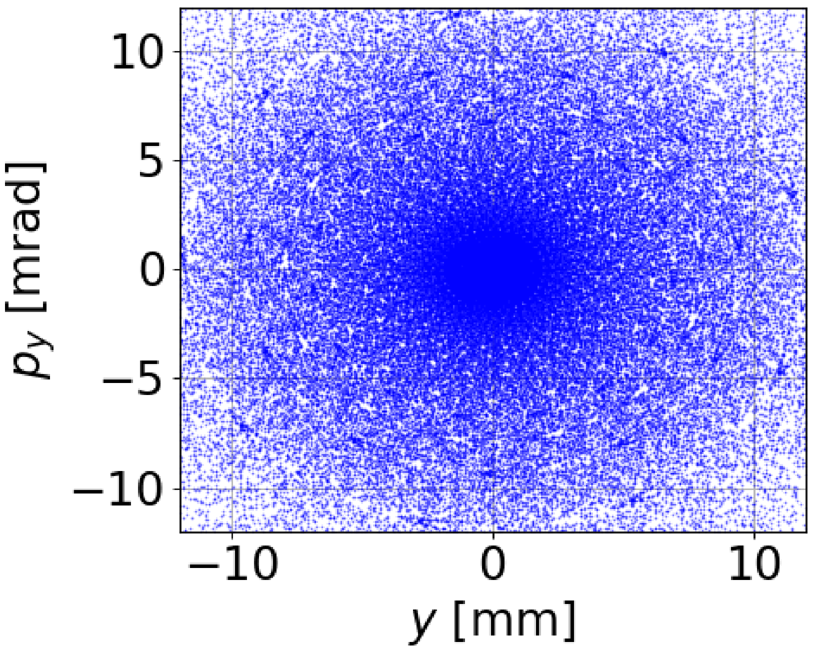
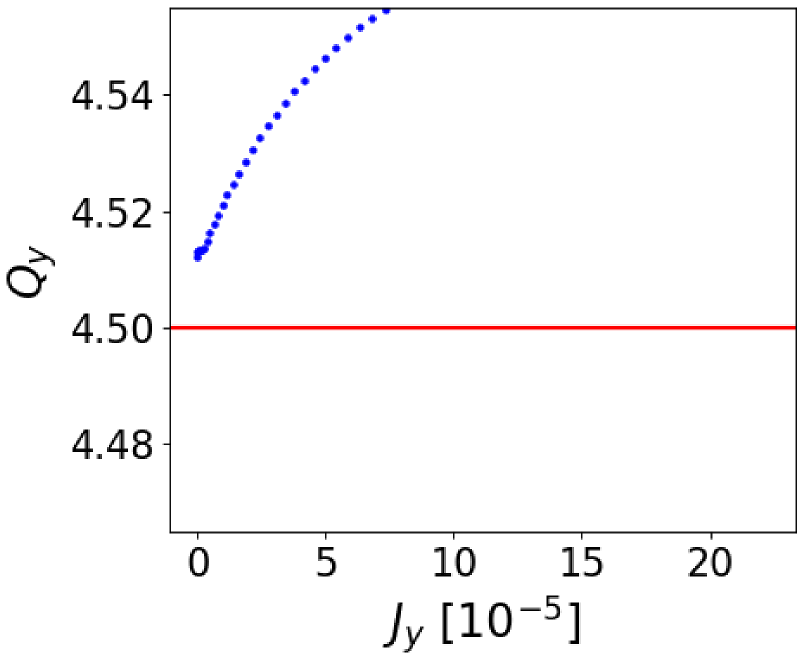
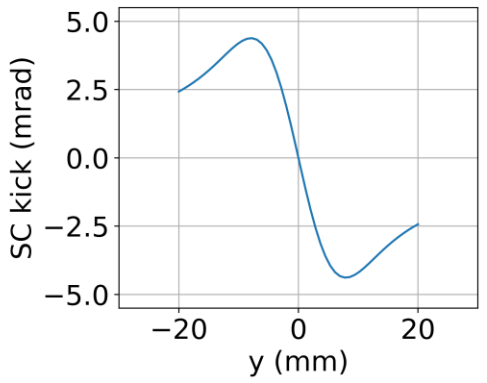
Toy-model of 1-D resonance crossing



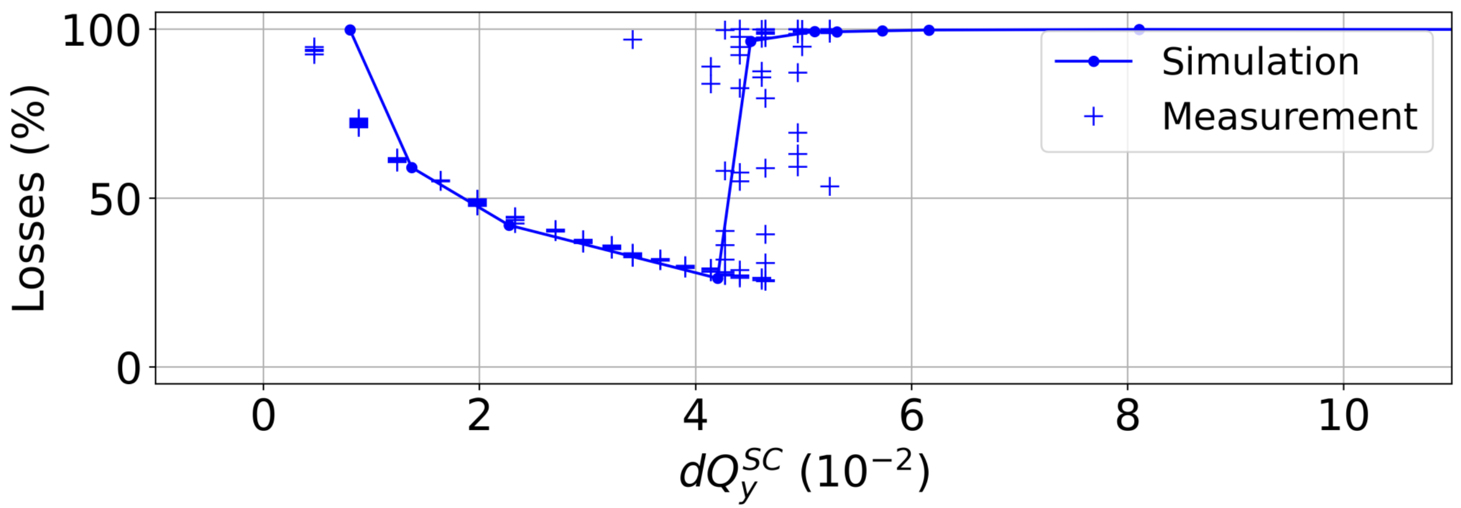




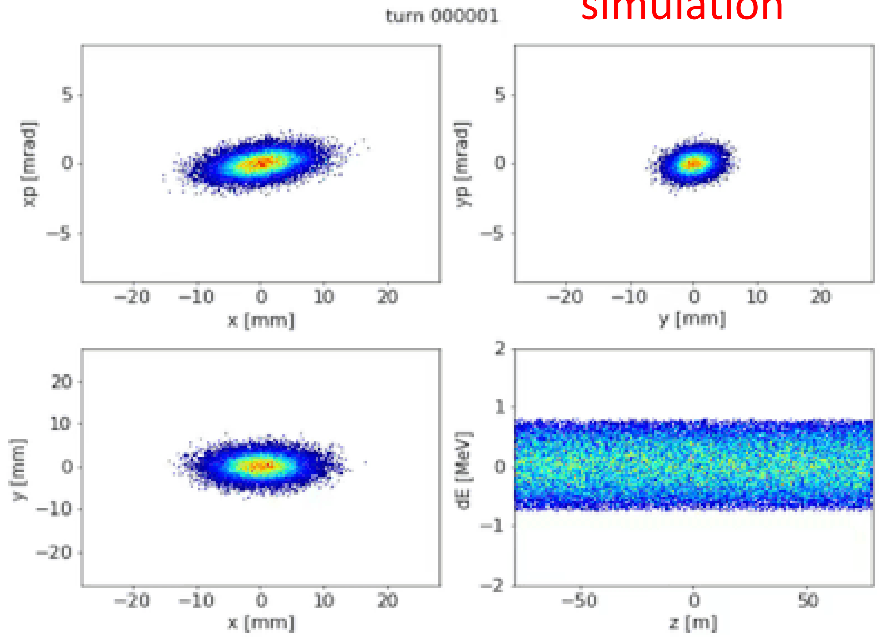
- 1-turn map + space charge kicks (amplitude detuning) + quadrupolar error (half-integer excitation).
- Appearance of stable resonance islands.
- The size of the islands depends on the excitation amplitude and the detuning gradient [9].
- During the dynamic crossing of the resonance, the islands move towards larger amplitudes.

Stronger space charge

- When the space charge is very strong and/or the crossing is very slow, the beam seems to get unstable both in measurements and simulations (beam is fully lost)!
- The exact reasons for this are not yet fully understood, both for measurements and simulations.
- Currently running simulations with other codes (Xsuite, Micromap, …).



PyOrbit simulation



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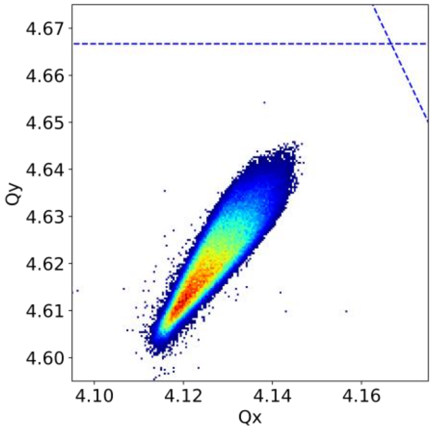
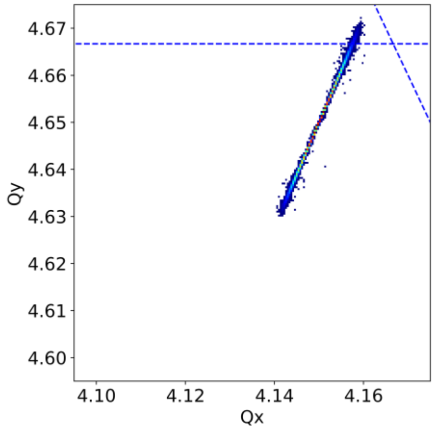
Increasing complexity

Chromaticity induces adittional detuning.

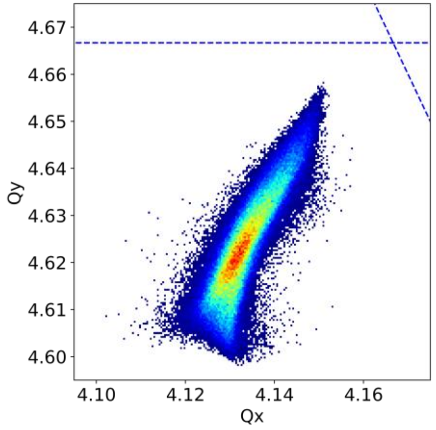
Space charge



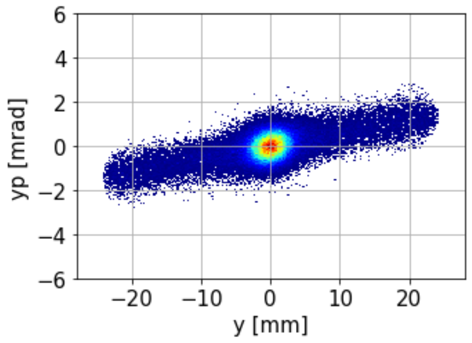
Chromaticity

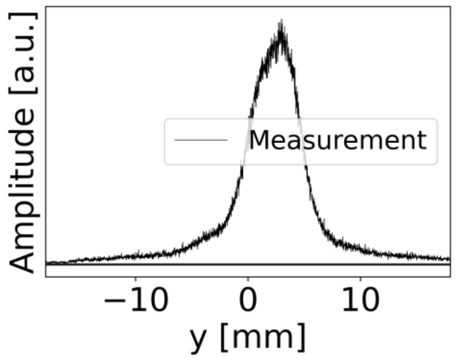


Space charge + chroma

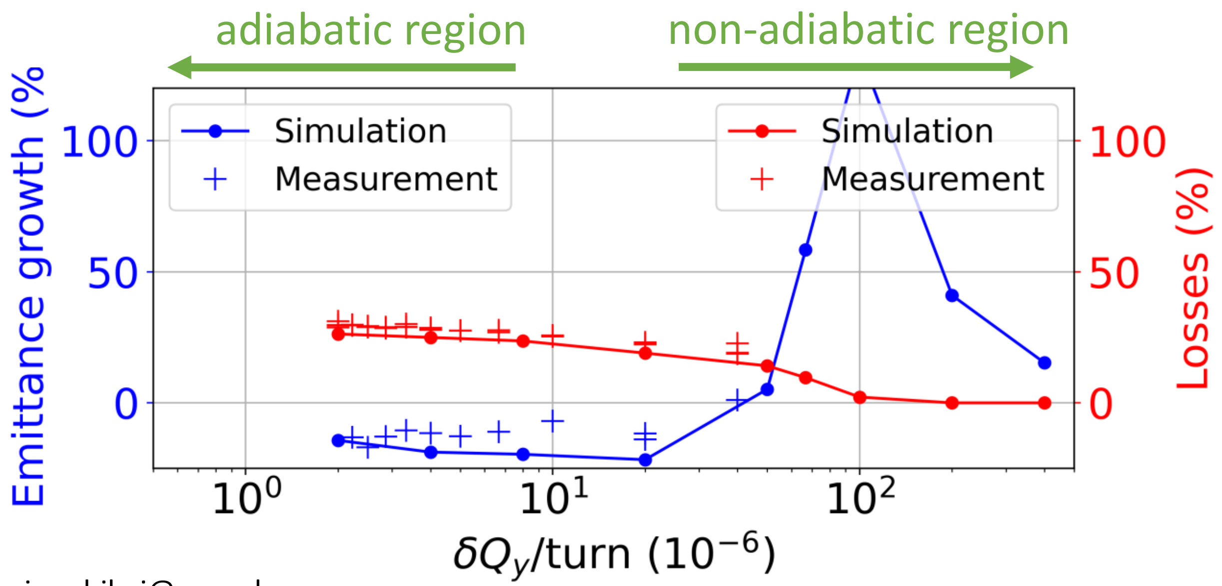


Appearance of multiple islands for different momentum offsets.





Beam effects change when crossing the resonance with different speeds.



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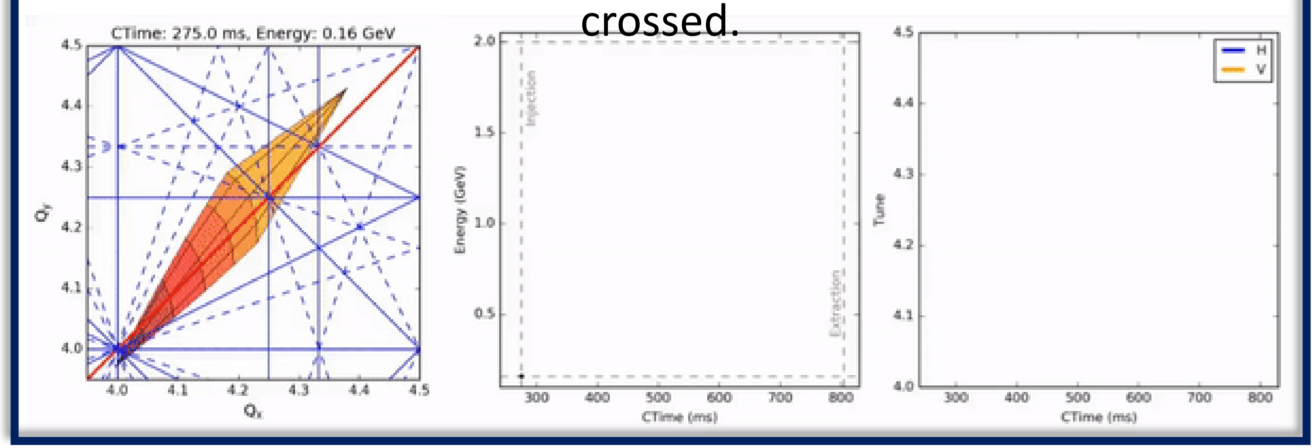
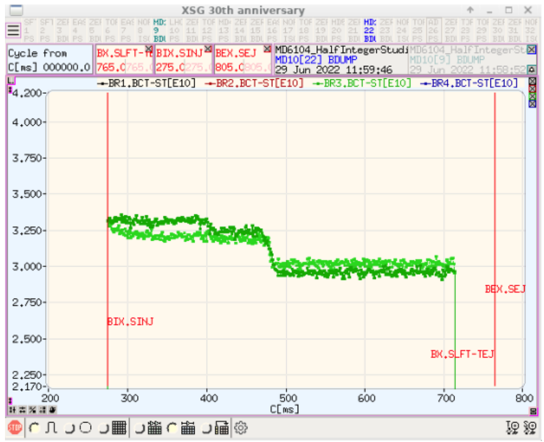
Increasing complexity even more: operational conditions

Beam is accelerated: space charge constantly changes. Higher order resonances are also crossed.

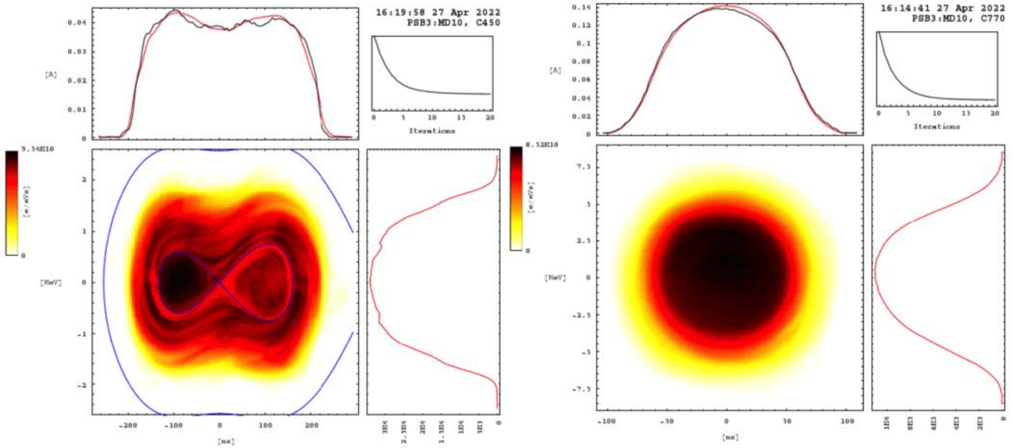


Half-integer is compensated but not perfectly (~3% losses).



Chromaticity cannot be corrected in both planes simultaneously.

Beam is bunched and goes from double harmonic to single harmonic.



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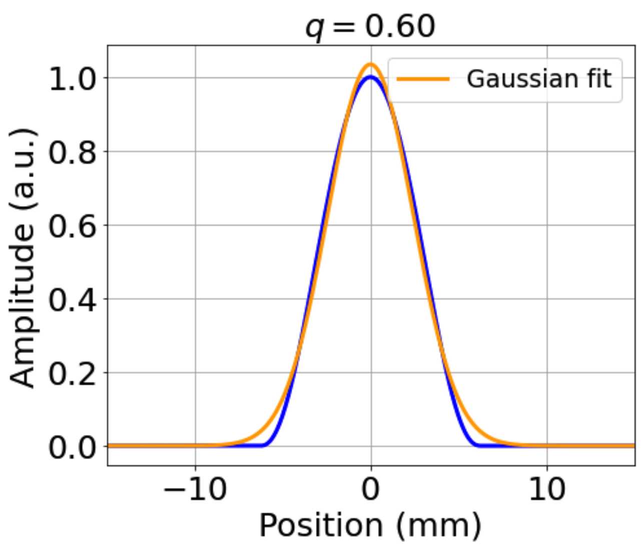
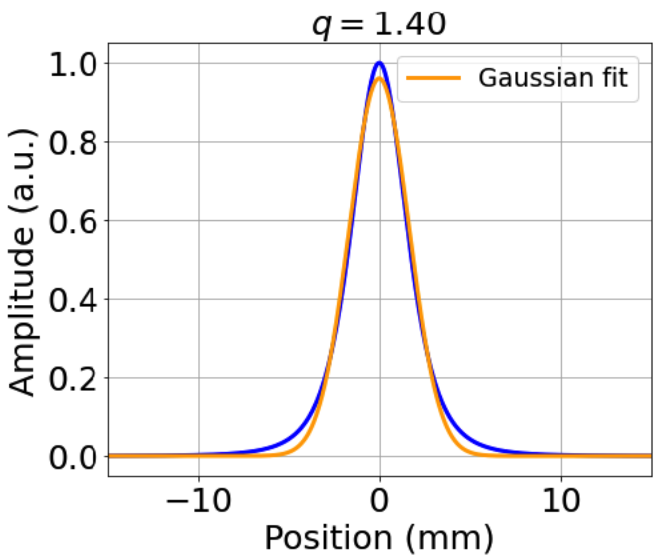
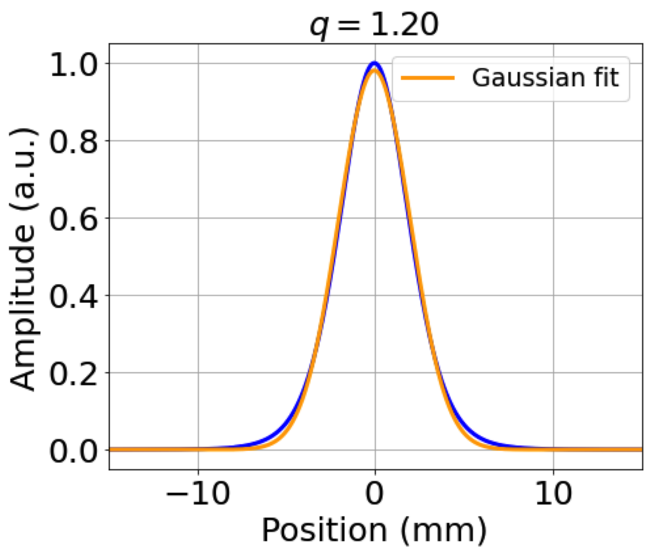
Modelling beam tails



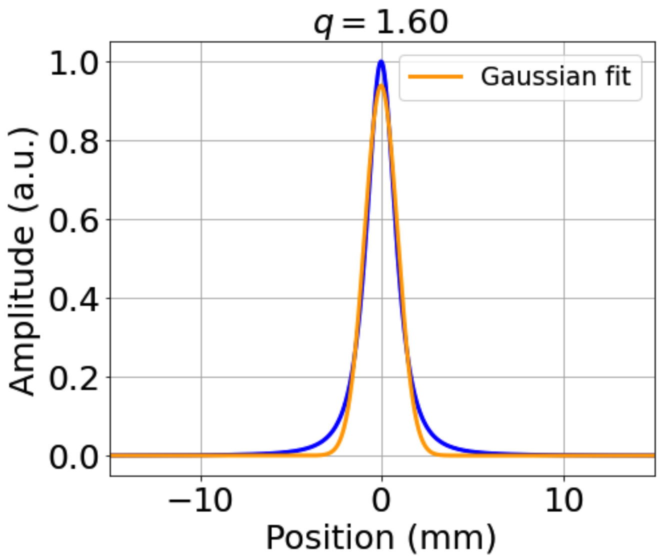


Generalized Gaussian function [5]:

$$f_{qG}(x; q, \beta) = \frac{\sqrt{\beta}}{C_q} e_q(-\beta x^2)$$



Used in the past to model non-Gaussian profiles in the LHC [6].



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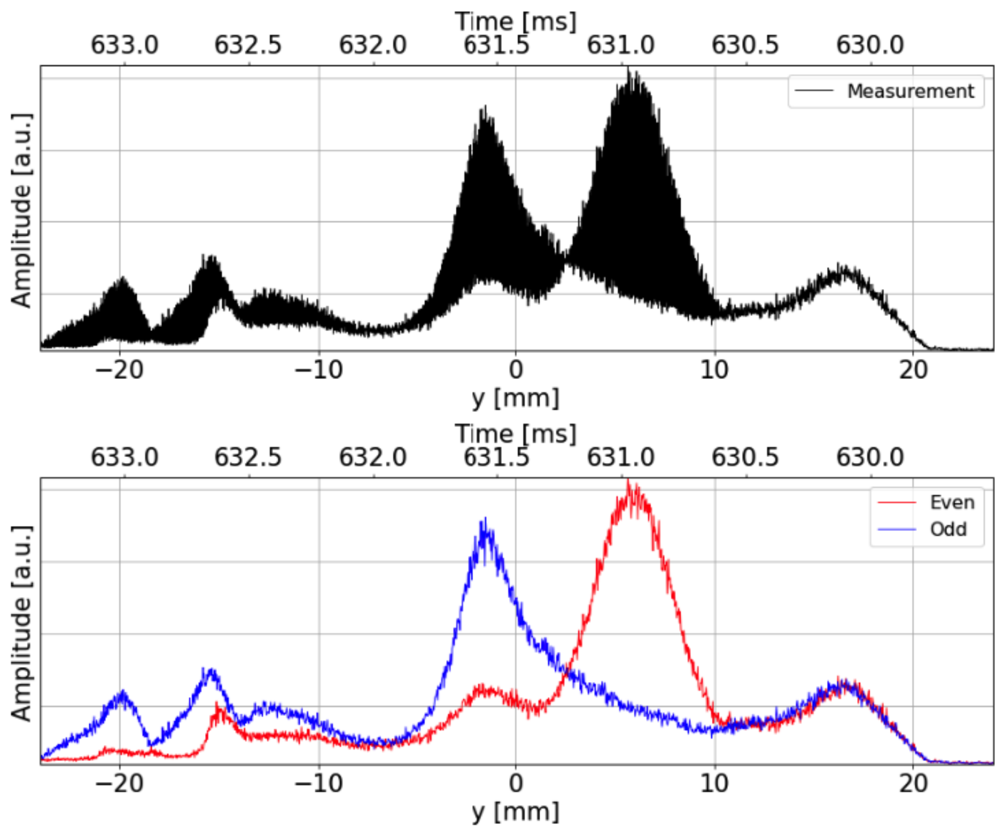
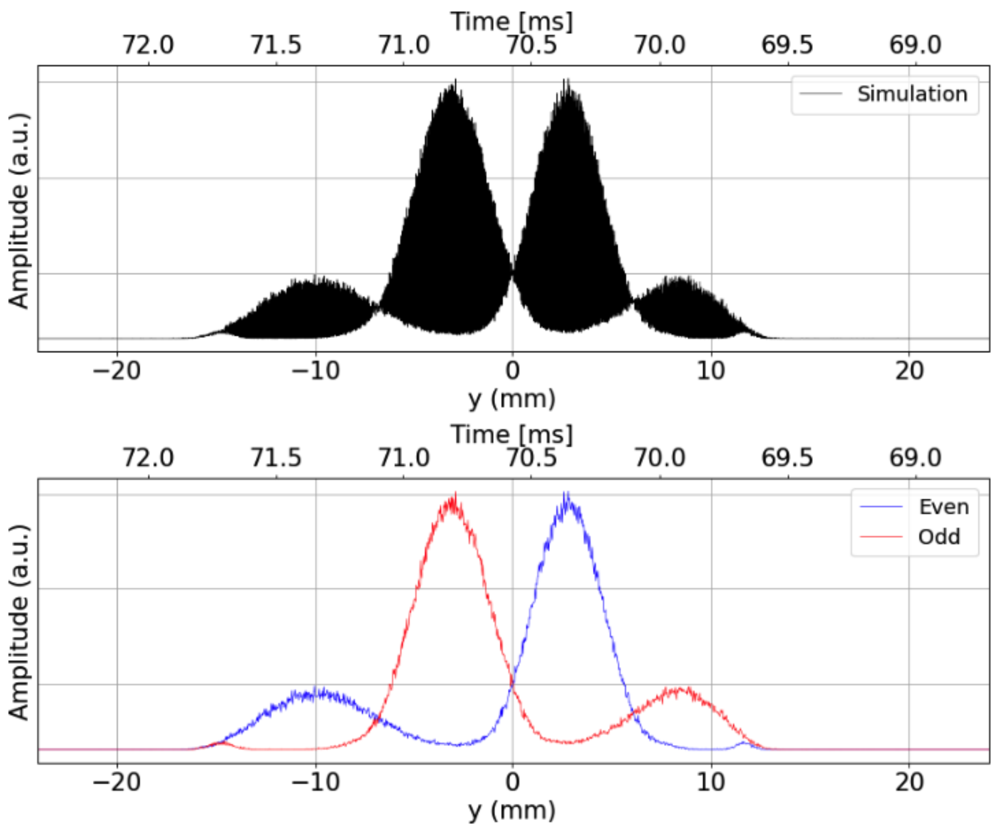
Profile measurement when beam is unstable

WS measurement



Simulating the WS in PyOrbit



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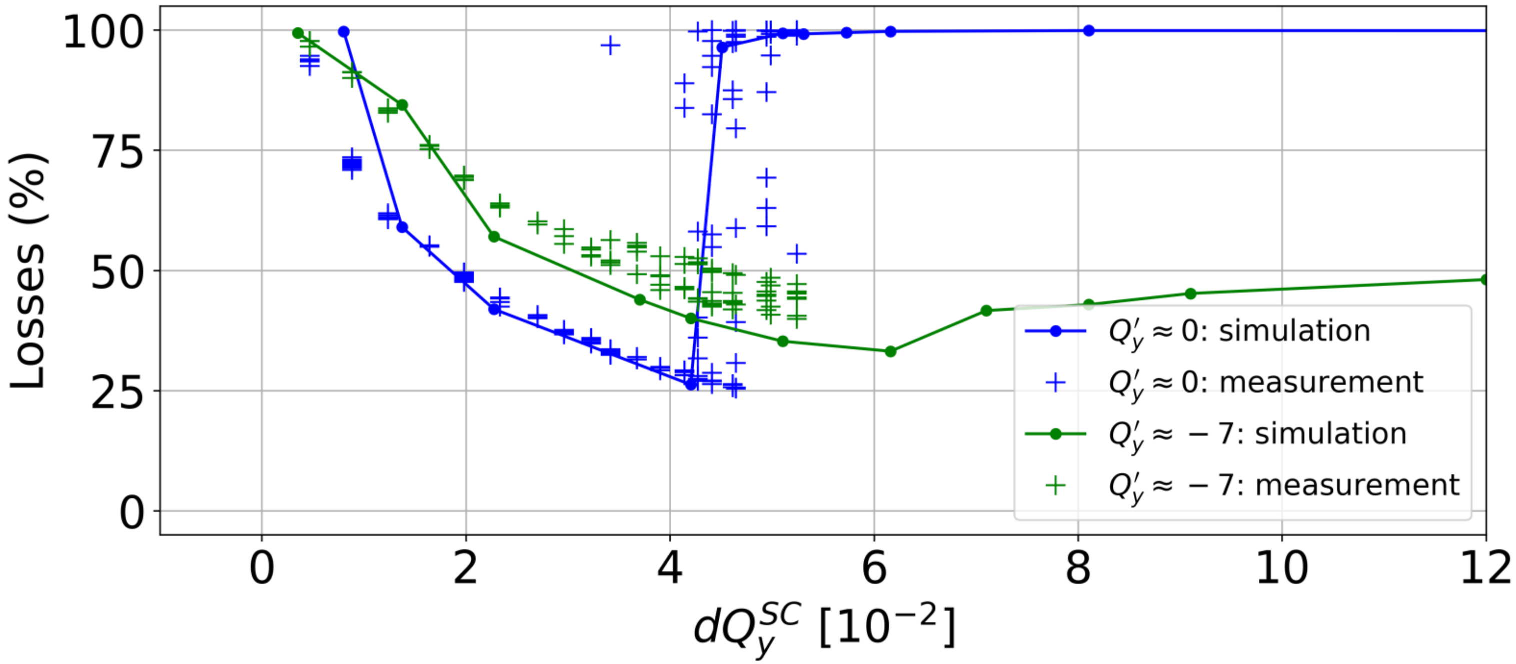
Effects of chromaticity



With non-zero chromaticity:

- More losses (the beam loss region increases).
- Beam not unstable for very strong space charge.

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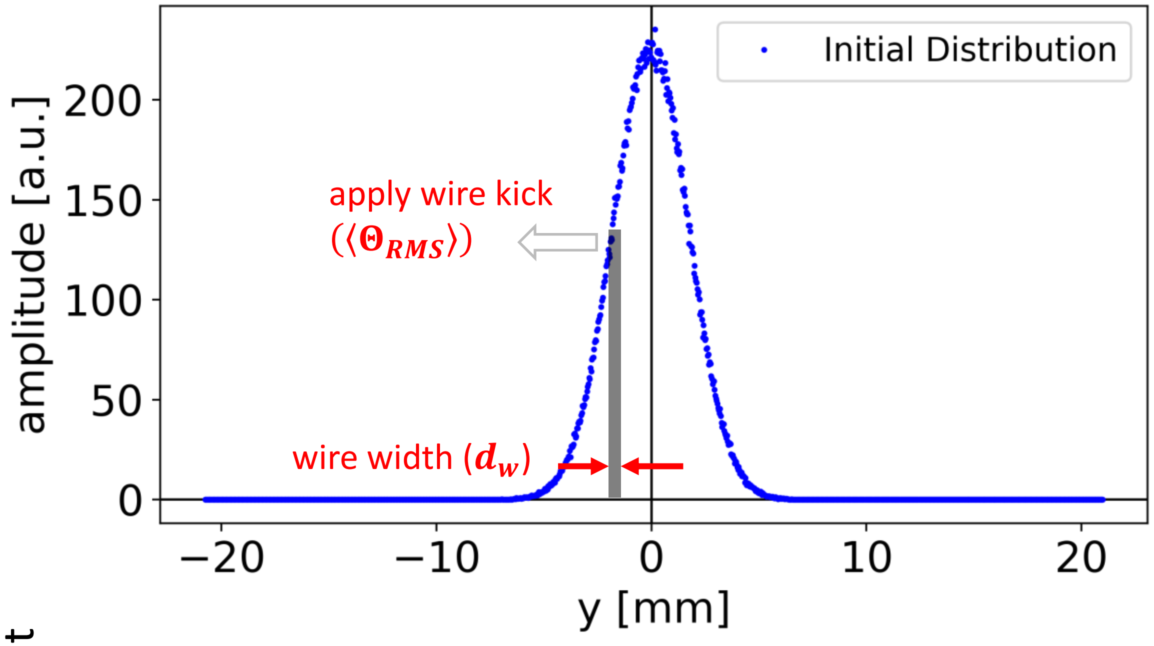
Modeling the Wire Scanner scattering

Apply the scattering kicks to the particles of the initial distribution that are within the wire width slice:

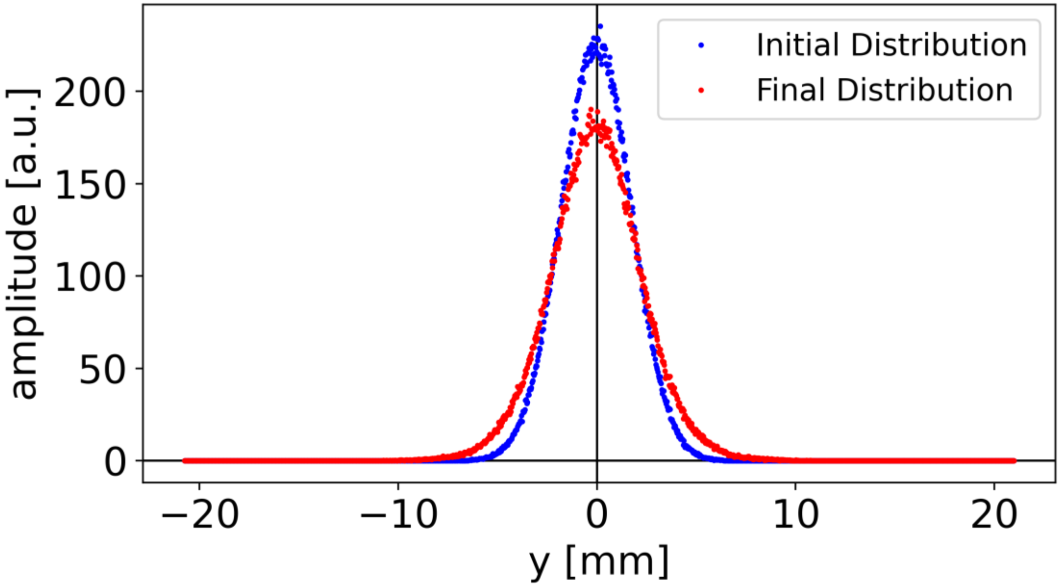


Track particles for one turn.

Displace the wire according to $\vec{R}$.

Repeat

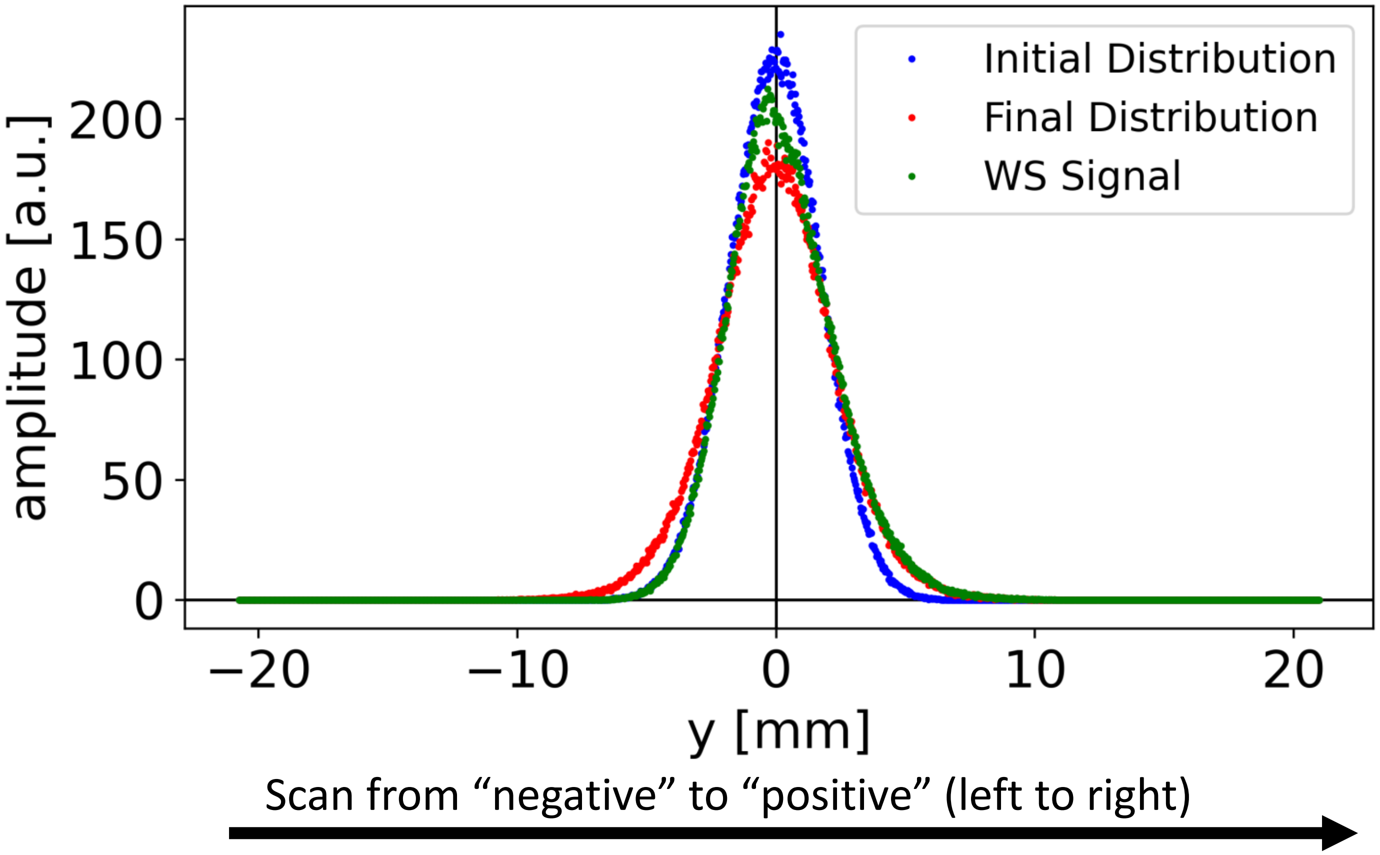
Final distribution: larger beam size because of the scattering.



Note that: simulation model independent of the beam intensity.

Modeling the Wire Scanner scattering

WS signal is proportional to the number of scattered particles → measured distribution (green) is between the initial and the final distribution



- In the first few turns of the scan, the WS signal coincides with the initial distribution.
- As the scan progresses, the particles are being scattered: towards the last turns of the scan, the WS signal coincides with the final distribution → asymmetric measured profile (WS Signal)

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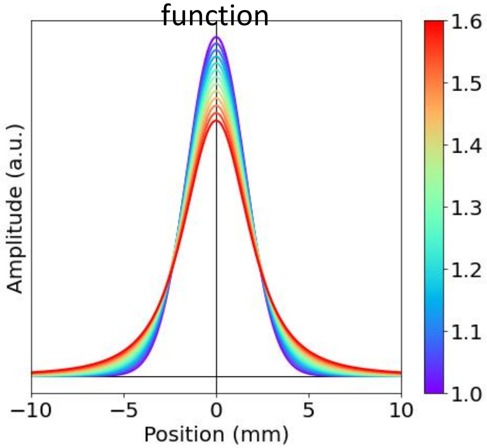
Shape of the particle distributions

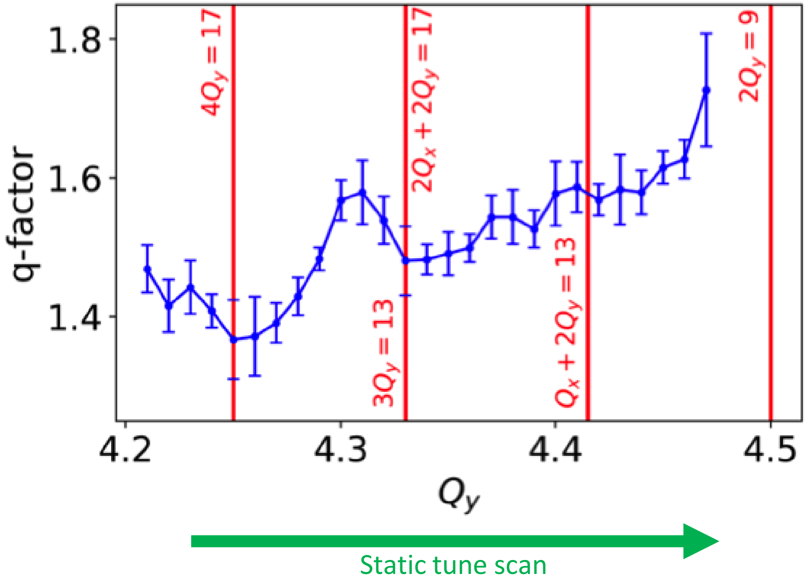
Experimental study on interplay between space charge and resonances on shape of particle distributions.

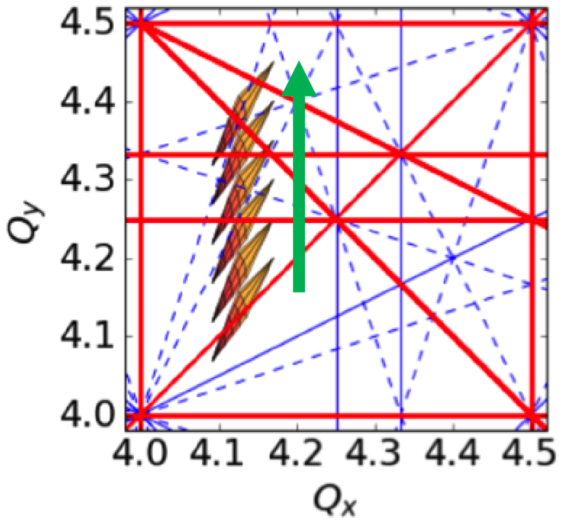
Modelling beam profiles' shape with q-Gaussian function



$q = 1.6$
Overpopulated tails
Undesirable!

$q = 1$
Gaussian shape
Desirable!





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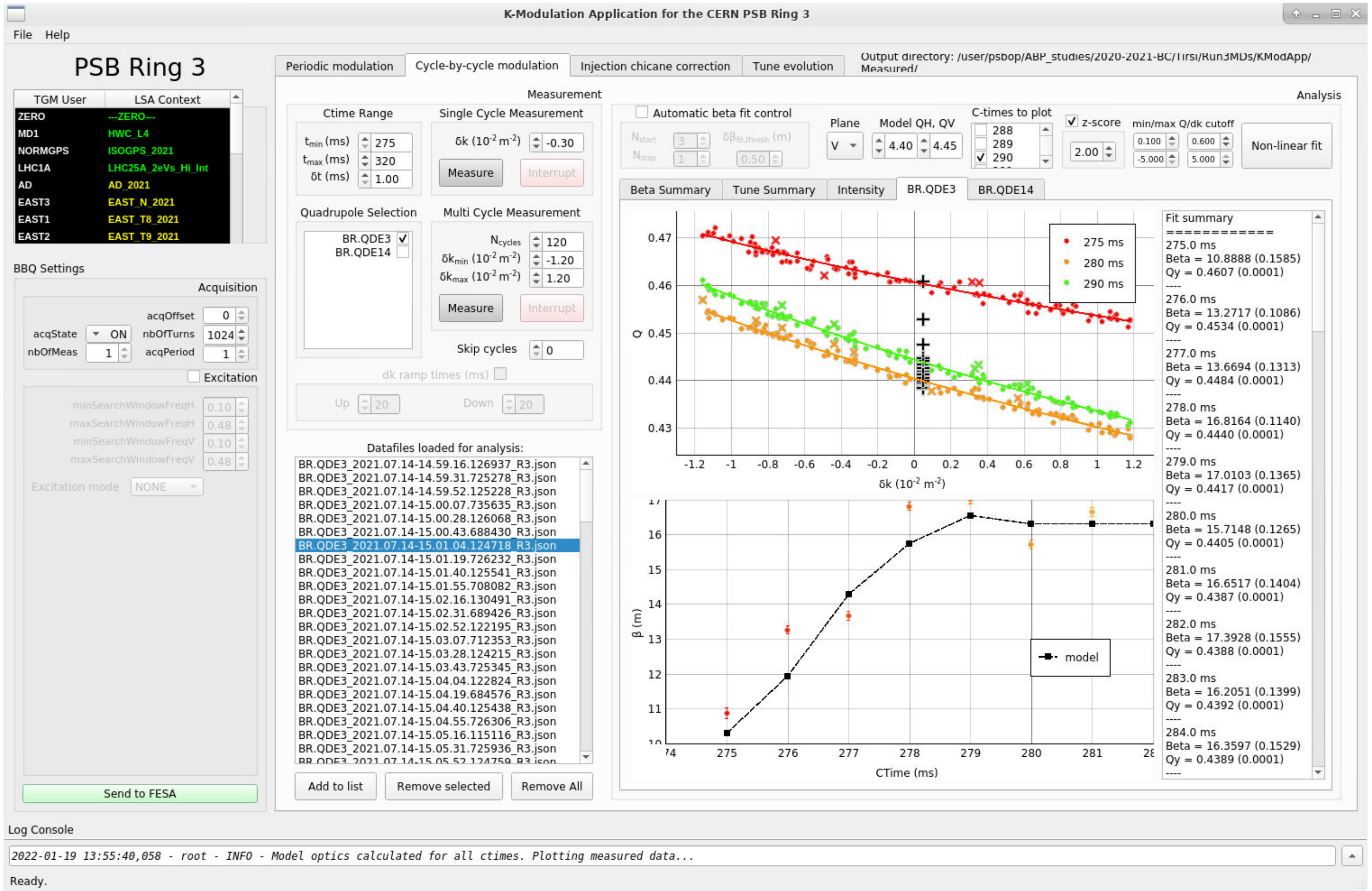
Operational implementation

Applicability of the method with respect to the:

- available instrumentation of the PSB
- hardware and software infrastructure
- technical limitations



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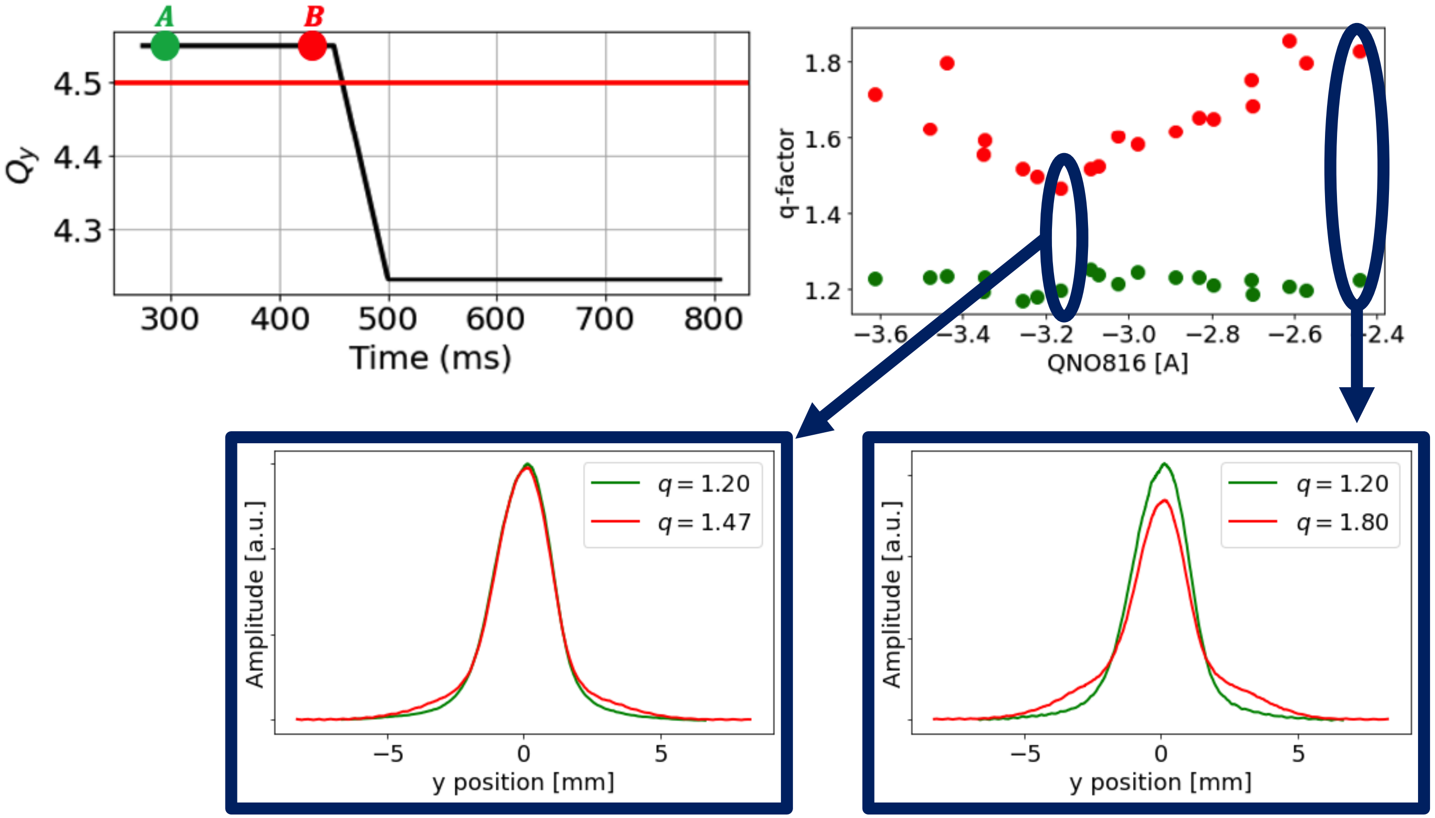
Half-integer resonance compensation and excitation

Resonance compensation:

- Experimentally, using orthogonal quadrupole correctors.
- Traditional techniques rely on crossing the resonance and monitoring the beam losses.
- Improved techniques were found that rely on the deformation of the shape of particle distribution (more sensitive!).



Resonance controlled excitation:

- In terms of deliberately degrading the compensation scheme.

Resonance width measurement:

- Finding methods to experimentally measure how large is the unstable region of the resonance.

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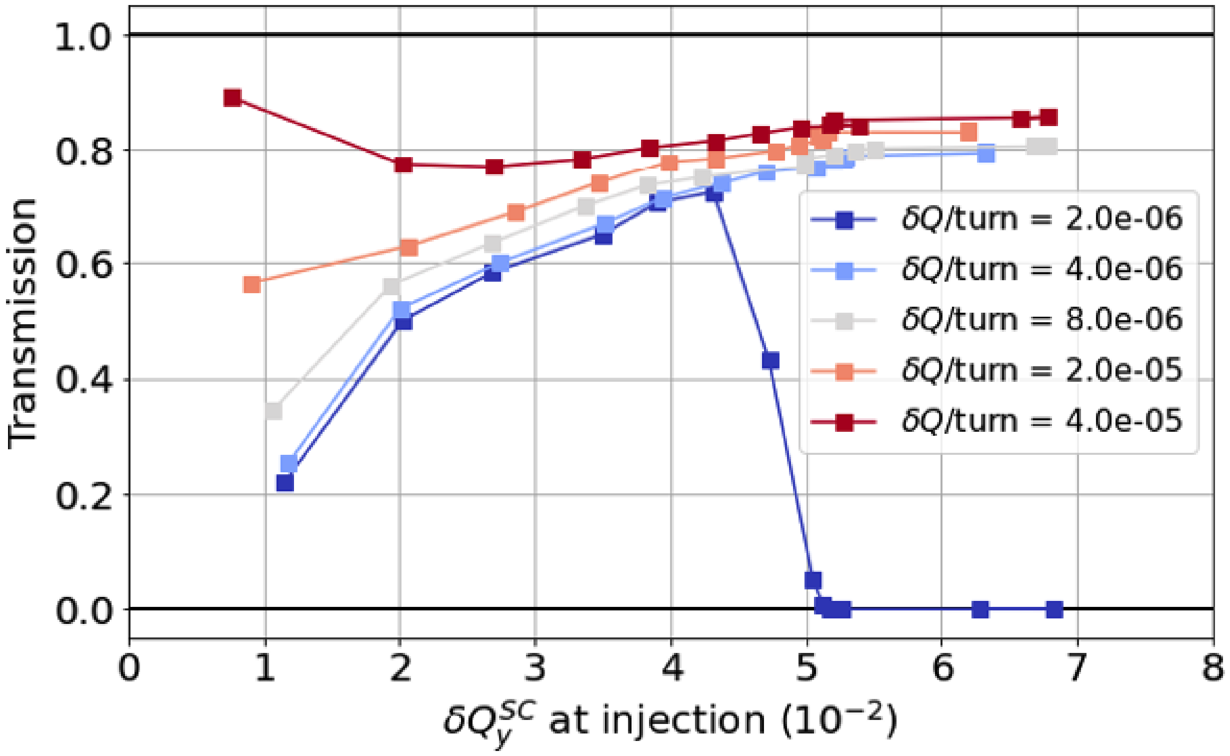
Universal scalling diagrams

Systematic scans on the half-integer dynamic crossing:

- Transmission: fraction of particles that survive the crossing
- δQ_y^{SC}: maximum space charge tune spread
- $\delta Q/turn$: vertical tune change over one turn ("crossing speed").



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